Chapter 7
Direct Physical Damage to Lifelines - Transportation Systems

This chapter describes the methodology for estimating direct physical damage to Transportation Systems, which include the following seven systems:

- Highway
- Railway
- Light Rail
- Bus
- Port
- Ferry
- Airport

The flowchart of the overall methodology, highlighting the transportation system module and its relationship to other modules, is shown in Flowchart 7.1.

7.1 Highway Transportation System

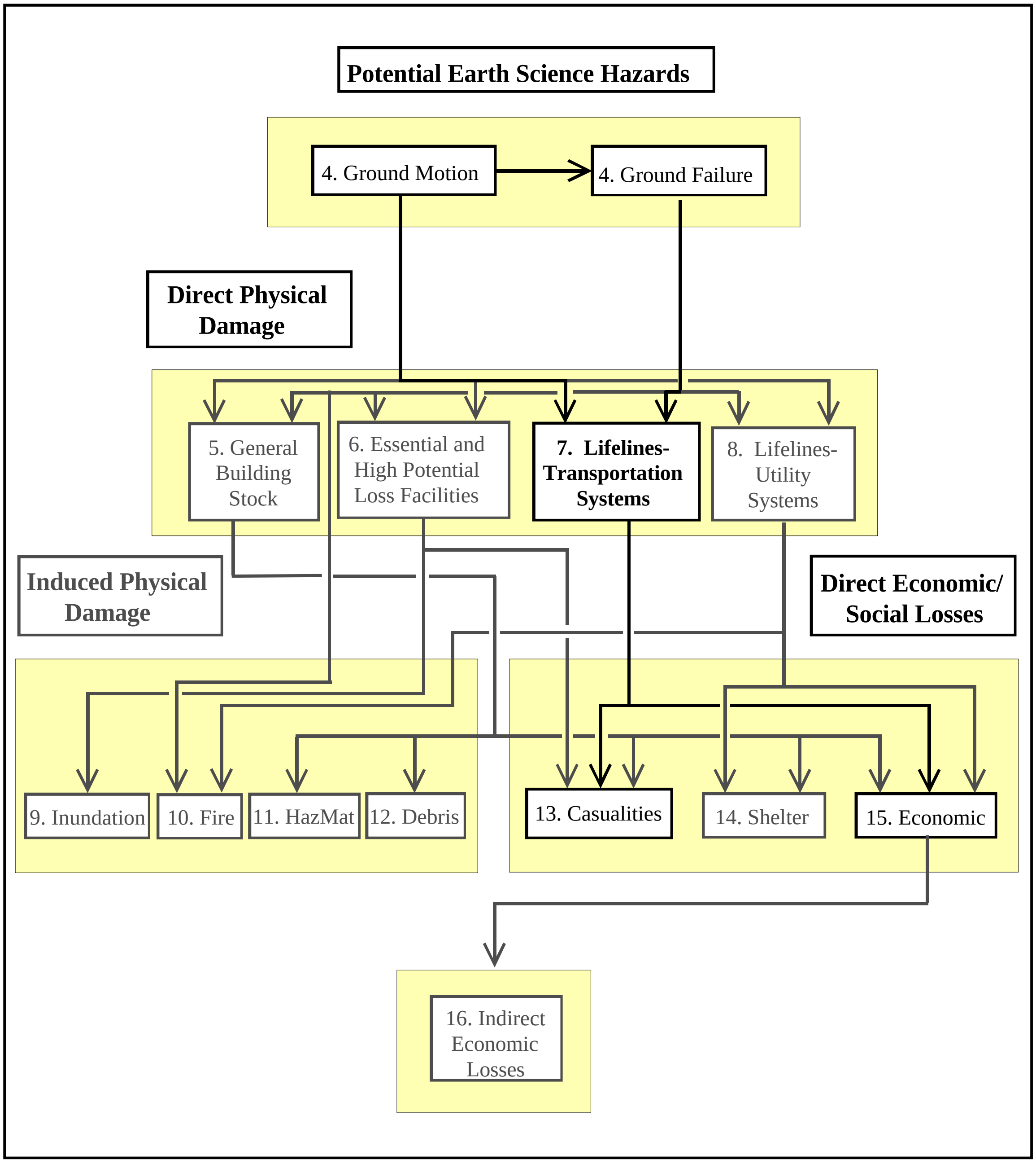
7.1.1 Introduction

This section presents an earthquake loss estimation methodology for a highway transportation system. This system consists of roadways, bridges and tunnels. Roads located on soft soil or fill or which cross a surface fault rupture can experience failure resulting in loss of functionality. Bridges that fail usually result in significant disruption to the transportation network, especially bridges that cross waterways. Likewise, tunnels are often not redundant, and major disruption to the transportation system is likely to occur should a tunnel become non-functional. Past earthquake damage reveals that bridges and tunnels are vulnerable to both ground shaking and ground failure, while roads are significantly affected by ground failure alone.

7.1.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a highway transportation system given knowledge of the system's components (i.e., roadways, bridges, or tunnels), the classification of each component (e.g., for roadways, whether the road is a major road or urban road), and the ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each highway system component are defined (i.e. slight/minor, moderate, extensive or complete). Damage states are related to a damage ratio defined as the ratio of repair to replacement cost for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For example, an extensively damaged roadway link might be closed (0% functional) immediately following the earthquake, but 100% functional after 30 days.



Flowchart 7.1 Transportation System Damage Relationship to Other Modules of the Earthquake Loss Estimation Methodology

Fragility curves are developed for each type of highway system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion.

7.1.3 Input Requirements and Output Information

Descriptions of required input to estimate damages to each highway system are given below.

Roadways

- Geographical location of roadway links (longitude and latitude of end nodes)
- Permanent ground deformation (PGD) at roadway link
- Roadway classification

Bridges

- Geographical location of bridge [longitude and latitude]
- Bridge classification
- Spectral accelerations at 0.3 sec and 1.0 sec, and PGD at bridge
- Peak Ground Acceleration (for PGD-related computations)

Tunnels

- Geographical location of tunnels [longitude and latitude]
- PGA and PGD at tunnel
- Tunnel Classification

Direct damage output for highway systems includes probability estimates of (1) component functionality and (2) physical damage expressed in terms of the component's damage ratio. Note that damage ratios, which are input to direct economic loss methods, are described in Chapter 15.

Component functionality is described by the probability of damage state (immediately following the earthquake) and by the associated fraction or percentage of the component that is expected to be functional after a specified period of time. For example, a roadway link might be found to have a 0.50 probability of extensive damage and on this basis would have a 0.50 probability that the road would be: (1) closed immediately, (2) partially open after a 3-day restoration period and (3) fully open after a 1-month restoration period.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a network system analysis that would be performed separately by a highway system expert.

7.1.4 Form of Damage Functions

Damage functions or fragility curves for all three highway system components mentioned above are modeled as lognormally-distributed functions that give the probability of reaching or exceeding different damage states for a given level of ground motion or ground failure. Each fragility curve is characterized by a median value of ground motion or ground failure and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (PGA) and ground failure is quantified in terms of permanent ground displacement (PGD).

- For roadways, fragility curves are defined in terms of PGD.
- For bridges, fragility curves are defined in terms of Sa (0.3 sec), Sa(1.0) and PGD.
- For tunnels, fragility curves are defined in terms of PGA and PGD.

Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the following sections.

7.1.5 Description of Highway Components

As mentioned previously, a highway system is composed of three components: roadways, bridges and tunnels. In this section, a brief description of each is given.

Roadways

Roadways are classified as major roads and urban roads. Major roads include interstate and state highways and other roads with four lanes or more. Parkways are also classified as major roads. Urban roads include intercity roads and other roads with two lanes.

Bridges

Bridges are classified based on the following structural characteristics:

- Seismic Design
- Number of spans: single vs. multiple span bridges
- Structure type: concrete, steel, others
- Pier type: multiple column bents, single column bents and pier walls
- Abutment type and bearing type: monolithic vs. non-monolithic; high rocker bearings, low steel bearings and neoprene rubber bearings
- Span continuity: continuous, discontinuous (in-span hinges), and simply supported.

The seismic design of a bridge is taken into account in terms of the (*i*) spectrum modification factor, (*ii*) strength reduction factor due to cyclic motion, (*iii*) drift limits, and (*iv*) the longitudinal reinforcement ratio.

This classification scheme incorporates various parameters that affect damage into fragility analysis and provides a means to obtain better fragility curves when data become available. A total of 28 classes (HWB1 through HWB28) are defined this way. These classes differentiate between the different bridge characteristics found in the National Bridge Inventory (NBI).

Tables 7.1.a and 7.1.b summarize the key NBI characteristics used, while Table 7.2 presents the 28 classes derived for HAZUS. Please refer to Table 3.6 in Chapter 3 for the full definitions of these bridges.

Table 7.1.a Bridge material Classes in NBI [NBI, 1988]

Code	Description
1	Concrete
2	Concrete continuous
3	Steel
4	Steel continuous
5	Prestressed concrete
6	Prestressed concrete continuous
7	Timber
8	Masonry
9	Aluminium, Wrought Iron, or Cast Iron
0	Other

Table 7.1.b Bridge Types in NBI [NBI, 1988]

Code	Description
01	Slab
02	Stringer/Multi-beam or Girder
03	Girder and Floor beam System
04	Tee Beam
05	Box Beam or Girders - Multiple
06	Box Beam or Girders – single or Spread
07	Frame
08	Orthotropic
09	Truss – Deck
10	Truss – Thru
11	Arch – Deck
12	Arch – Thru
13	Suspension
14	Stayed Girder
15	Movable – Lift
16	Movable – Bascule
17	Movable – Swing
18	Tunnel
19	Culvert
20	Mixed Types (applicable only to approach spans)
21	Segmental Box Girder
22	Channel Beam
00	Other

Table 7.2 HAZUS Bridge Classification Scheme

CLASS	NBI Class	State	Year Built	# Spans	Length of Max. Span (meter)	Length less than 20 m	K_{3D} (See note below)	I_{shape} (See note below)	Design	Description
HWB1	All	Non-CA	< 1990		> 150	N/A	EQ1	0	Conventional	Major Bridge - Length > 150m
HWB1	All	CA	< 1975		> 150	N/A	EQ1	0	Conventional	Major Bridge - Length > 150m
HWB2	All	Non-CA	>= 1990		> 150	N/A	EQ1	0	Seismic	Major Bridge - Length > 150m
HWB2	All	CA	>= 1975		> 150	N/A	EQ1	0	Seismic	Major Bridge - Length > 150m
HWB3	All	Non-CA	< 1990	1		N/A	EQ1	1	Conventional	Single Span
HWB3	All	CA	< 1975	1		N/A	EQ1	1	Conventional	Single Span
HWB4	All	Non-CA	>= 1990	1		N/A	EQ1	1	Seismic	Single Span
HWB4	All	CA	>= 1975	1		N/A	EQ1	1	Seismic	Single Span
HWB5	101-106	Non-CA	< 1990			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support - Concrete
HWB6	101-106	CA	< 1975			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support - Concrete
HWB7	101-106	Non-CA	>= 1990			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Concrete
HWB7	101-106	CA	>= 1975			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Concrete
HWB8	205-206	CA	< 1975			N/A	EQ2	0	Conventional	Single Col., Box Girder - Continuous Concrete
HWB9	205-206	CA	>= 1975			N/A	EQ3	0	Seismic	Single Col., Box Girder - Continuous Concrete
HWB10	201-206	Non-CA	< 1990			N/A	EQ2	1	Conventional	Continuous Concrete
HWB10	201-206	CA	< 1975			N/A	EQ2	1	Conventional	Continuous Concrete
HWB11	201-206	Non-CA	>= 1990			N/A	EQ3	1	Seismic	Continuous Concrete
HWB11	201-206	CA	>= 1975			N/A	EQ3	1	Seismic	Continuous Concrete
HWB12	301-306	Non-CA	< 1990			No	EQ4	0	Conventional	Multi-Col. Bent, Simple Support - Steel
HWB13	301-306	CA	< 1975			No	EQ4	0	Conventional	Multi-Col. Bent, Simple Support - Steel
HWB14	301-306	Non-CA	>= 1990			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Steel
HWB14	301-306	CA	>= 1975			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Steel
HWB15	402-410	Non-CA	< 1990			No	EQ5	1	Conventional	Continuous Steel
HWB15	402-410	CA	< 1975			No	EQ5	1	Conventional	Continuous Steel
HWB16	402-410	Non-CA	>= 1990			N/A	EQ3	1	Seismic	Continuous Steel
HWB16	402-410	CA	>= 1975			N/A	EQ3	1	Seismic	Continuous Steel

Table 7.2 HAZUS Bridge Classification Scheme (Continued)

CLASS	NBI Class	State	Year Built	# Spans	Length of Max. Span (meter)	Length less than 20 m	K_{3D} (See note below)	I_{shape} (See note below)	Design	Description
HWB17	501-506	Non-CA	< 1990			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support - Prestressed Concrete
HWB18	501-506	CA	< 1975			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support - Prestressed Concrete
HWB19	501-506	Non-CA	>= 1990			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Prestressed Concrete
HWB19	501-506	CA	>= 1975			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Prestressed Concrete
HWB20	605-606	CA	< 1975			N/A	EQ2	0	Conventional	Single Col., Box Girder - Prestressed Continuous Concrete
HWB21	605-606	CA	>= 1975			N/A	EQ3	0	Seismic	Single Col., Box Girder - Prestressed Continuous Concrete
HWB22	601-607	Non-CA	< 1990			N/A	EQ2	1	Conventional	Continuous Concrete
HWB22	601-607	CA	< 1975			N/A	EQ2	1	Conventional	Continuous Concrete
HWB23	601-607	Non-CA	>= 1990			N/A	EQ3	1	Seismic	Continuous Concrete
HWB23	601-607	CA	>= 1975			N/A	EQ3	1	Seismic	Continuous Concrete
HWB24	301-306	Non-CA	< 1990			Yes	EQ6	0	Conventional	Multi-Col. Bent, Simple Support - Steel
HWB25	301-306	CA	< 1975			Yes	EQ6	0	Conventional	Multi-Col. Bent, Simple Support - Steel
HWB26	402-410	Non-CA	< 1990			Yes	EQ7	1	Conventional	Continuous Steel
HWB27	402-410	CA	< 1975			Yes	EQ7	1	Conventional	Continuous Steel
HWB28										All other bridges that are not classified

Note that EQ1 through EQ7 in Table 7.2 are equations for evaluating K_{3D}, which is a factor that modifies the piers' 2-dimensional capacity allowing for 3-dimensional arch action in the deck. All these equations have the functional form of:

$$K_{3D} = 1 + A / (N - B)$$

Where N is the number of spans and A and B are given in table 7.3.

Also note that I_{shape} in table 7.2 is a Boolean indicator. When $I_{shape} = 0$, then the K_{shape} factor, which is a modifier that converts cases for short periods to an equivalent spectral amplitude at T=1.0 second, does not apply. On the other hand, When $I_{shape} = 1$, then the K_{shape} factor applies. Later in this section, the use of the K_{shape} factor will be illustrated through an example.

It is important to remember that the 28 bridge classes in Table 7.2 (HWB1 through HWB28) reflect the maximum number of combinations for 'standard' bridge classes. Attributes such as the skeweness and number of spans are further accounted for in the evaluation of damage potential through a modification scheme that is presented later in this section.

Table 7.3 Coefficients for Evaluating K_{3D}

Equation	A	B	K_{3D}
EQ1	0.25	1	1 + 0.25 / (N – 1)
EQ2	0.33	0	1 + 0.33 / (N)
EQ3	0.33	1	1 + 0.33 / (N – 1)
EQ4	0.09	1	1 + 0.09 / (N – 1)
EQ5	0.05	0	1 + 0.05 / (N)
EQ6	0.20	1	1 + 0.20 / (N – 1)
EQ7	0.10	0	1 + 0.10 / (N)

Tunnels

Tunnels are classified as bored/drilled or cut & cover.

7.1.6 Definitions of Damage States

A total of five damage states are defined for highway system components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

Slight/Minor Damage (ds_2)

- For roadways, ds_2 is defined by slight settlement (few inches) or offset of the ground.

- For bridges, ds_2 is defined by minor cracking and spalling to the abutment, cracks in shear keys at abutments, minor spalling and cracks at hinges, minor spalling at the column (damage requires no more than cosmetic repair) or minor cracking to the deck

- For tunnels, ds_2 is defined by minor cracking of the tunnel liner (damage requires no more than cosmetic repair) and some rock falling, or by slight settlement of the ground at a tunnel portal.

Moderate Damage (ds_3)

- For roadways, ds_3 is defined by moderate settlement (several inches) or offset of the ground.

- For bridges, ds_3 is defined by any column experiencing moderate (shear cracks) cracking and spalling (column structurally still sound), moderate movement of the abutment (<2"), extensive cracking and spalling of shear keys, any connection having cracked shear keys or bent bolts, keeper bar failure without unseating, rocker bearing failure or moderate settlement of the approach.

- For tunnels, ds_3 is defined by moderate cracking of the tunnel liner and rock falling.

Extensive Damage (ds_4)

- For roadways, ds_4 is defined by major settlement of the ground (few feet).

- For bridges, ds_4 is defined by any column degrading without collapse – shear failure - (column structurally unsafe), significant residual movement at connections, or major settlement approach, vertical offset of the abutment, differential settlement at connections, shear key failure at abutments.

- For tunnels, ds_4 is characterized by major ground settlement at a tunnel portal and extensive cracking of the tunnel liner.

Complete Damage (ds_5)

- For roadways, ds_5 is defined by major settlement of the ground (i.e., same as ds_4).

- For bridges, ds_5 is defined by any column collapsing and connection losing all bearing support, which may lead to imminent deck collapse, tilting of substructure due to foundation failure.

- For tunnels, ds_5 is characterized by major cracking of the tunnel liner, which may include possible collapse.

7.1.7 Component Restoration Curves

Restoration curves are developed based on a best fit to ATC-13 data for the social function classifications of interest (SF 25a through SF 25e) consistent with damage states defined in the previous section (first four classes in ATC-13). Figure 7.1 shows restoration curves for urban and major roads, Figure 7.2 represents restoration curves for highway bridges, while Figure 7.3 shows restoration curves for highway tunnels. The smooth curves shown in these figures are normal curves characterized by a mean and a standard deviation. The parameters of these restoration curves are given in Tables 7.4 and 7.5. The former table gives means and standard deviations for each restoration curve (i.e., smooth continuous curve), while the second table gives approximate discrete functions for the restoration curves developed.

Table 7.4 Continuous Restoration Functions for Highways (after ATC-13, 1985)

Damage State	Roadways		Highway Bridges		Highway Tunnels	
	Mean (Days)	σ (days)	Mean (Days)	σ (days)	Mean (Days)	σ (days)
Slight/Minor	0.9	0.05	0.6	0.6	0.5	0.3
Moderate	2.2	1.8	2.5	2.7	2.4	2.0
Extensive	21	16	75.0	42.0	45.0	30.0
Complete			230.0	110.0	210.0	110.0

The values shown in Table 7.5 below represent distributions on functionality for each restoration period based on damage state immediately after the earthquake.

Table 7.5 Discrete Restoration Functions for Highways

Roadways

Restoration Period	Functional Percentage		
	Slight	Moderate	Extensive/Complete
1 day	90	25	10
3 days	100	65	14
7 days	100	100	20
30 days	100	100	70
90 days	100	100	100

Bridges

Restoration Period	Functional Percentage			
	Slight	Moderate	Extensive	Complete
1 day	70	30	2	0
3 days	100	60	5	2
7 days	100	95	6	2
30 days	100	100	15	4
90 days	100	100	65	10

Tunnels

Restoration Period	Functional Percentage			
	Slight	Moderate	Extensive	Complete
1 day	90	25	5	0
3 days	100	65	8	3
7 days	100	100	10	3
30 days	100	100	30	5
90 days	100	100	95	15

7.1.8 Development of Damage Functions

Fragility curves for highway system components are defined with respect to classification and ground motion parameter.

Damage functions for Roadways

Fragility curves for major roads and urban roads are shown in Figures 7.4. and 7.5, respectively. The medians and dispersions of these curves are presented in Table 7.6.

Table 7.6 Damage Algorithms for Roadways

Permanent Ground Deformation			
Components	**Damage State**	**Median (in)**	**β**
Major Road (Hrd1)	slight/minor	12	0.7
	moderate	24	0.7
	extensive/complete	60	0.7
Urban Roads (Hrd2)	slight/minor	6	0.7
	moderate	12	0.7
	extensive/complete	24	0.7

Damage Functions for Bridges

There are 28 primary bridge types for which all four damage states are identified and described. For other bridges, fragility curves of the 28 primary bridge types are adjusted to reflect a diminished or improved level of expected performance.

A total of 224 bridge damage functions are obtained, 116 due to ground shaking and 116 due to ground failure. For more information on the theoretical background in the derivation of these fragility curves, consult the work done by ***Basoz and Mander (1999)***, which is referenced at the end of this section and which can obtained from NIBS.

Medians of these damage functions are given in Table 7.7. Note that the dispersion is set to 0.4 for the ground shaking damage algorithm and 0.2 for the ground failure damage algorithm. Also note that only incipient unseating and collapse (i.e., which correspond to extensive and complete damage states) are considered as the possible types of damage due to ground failure. That is, initial damage to bearings (i.e., which would correspond to slight and/or moderate damage states) from ground failure is not considered.

Figures 7.6 and 7.7 show example fragility curves for major bridges.

Table 7.7 Damage Algorithms for Bridges

	Sa [1.0 sec in g's] for Damage Functions due to Ground Shaking				PGD [inches] for Damage Functions due to Ground Failure			
CLASS	Slight	Moderate	Extensive	Complete	Slight	Moderate	Extensive	Complete
HWB1	0.4	0.5	0.6	0.8	7.9	7.9	7.9	15.7
HWB2	0.6	0.8	1	1.6	31.5	31.5	31.5	35.4
HWB3	0.8	0.9	1.1	1.6	3.9	3.9	3.9	17.7
HWB4	0.8	0.9	1.1	1.6	3.9	3.9	3.9	17.7
HWB5	0.26	0.35	0.44	0.65	3.9	3.9	3.9	13.8
HWB6	0.33	0.46	0.56	0.83	3.9	3.9	3.9	13.8
HWB7	0.45	0.76	1.05	1.53	3.9	3.9	3.9	13.8
HWB8	0.35	0.42	0.5	0.74	3.9	3.9	3.9	5.9
HWB9	0.54	0.88	1.22	1.45	23.6	23.6	23.6	35.4
HWB10	0.6	0.79	1.05	1.38	3.9	3.9	3.9	5.9
HWB11	0.91	0.91	1.05	1.38	23.6	23.6	23.6	35.4
HWB12	0.26	0.35	0.44	0.65	3.9	3.9	3.9	13.8
HWB13	0.33	0.46	0.56	0.83	3.9	3.9	3.9	13.8
HWB14	0.45	0.76	1.05	1.53	3.9	3.9	3.9	13.8
HWB15	0.76	0.76	0.76	1.04	3.9	3.9	3.9	9.8
HWB16	0.91	0.91	1.05	1.38	5.9	5.9	5.9	11.8
HWB17	0.26	0.35	0.44	0.65	3.9	3.9	3.9	13.8
HWB18	0.33	0.46	0.56	0.83	3.9	3.9	3.9	13.8
HWB19	0.45	0.76	1.05	1.53	3.9	3.9	3.9	13.8
HWB20	0.35	0.42	0.5	0.74	3.9	3.9	3.9	5.9
HWB21	0.54	0.88	1.22	1.45	23.6	23.6	23.6	35.4
HWB22	0.6	0.79	1.05	1.38	3.9	3.9	3.9	5.9
HWB23	0.91	0.91	1.05	1.38	23.6	23.6	23.6	35.4
HWB24	0.26	0.35	0.44	0.65	3.9	3.9	3.9	13.8
HWB25	0.33	0.46	0.56	0.83	3.9	3.9	3.9	13.8
HWB26	0.76	0.76	0.76	1.04	3.9	3.9	3.9	9.8
HWB27	0.76	0.76	0.76	1.04	3.9	3.9	3.9	9.8
HWB28	0.8	0.9	1.1	1.6	3.9	3.9	3.9	17.7

The damage algorithm for bridges can be broken into seven steps:

Step 1:
Get the bridge location (longitude and latitude), class (HWB1 through HWB28), number of spans (N), skew angle (α), span width (W), bridge length (L), and maximum span length (L_{max}). Note that the skew angle is defined as the angle between the centerline of a pier and a line normal to the roadway centerline.

Step 2:
Evaluate the soil-amplified shaking at the bridge site. That is, get the peak ground acceleration (PGA), spectral accelerations (Sa[0.3 sec] and Sa[1.0 sec]) and the permanent ground deformation (PGD).

Step 3:
Evaluate the following three modification factors:

K_{skew} = sqrt[sin(90-α)]

K_{shape} = 2.5 x Sa(1.0 sec) / Sa(0.3 sec)

K_{3D} = 1 + A / (N – B)   A and B are read from Table 7.3

Step 4:
Modify the ground shaking medians for the "standard" fragility curves in Table 7.7 as follows:

New Median [for slight] = Old Median [for slight] x $Factor_{slight}$

Where
$Factor_{slight}$ = 1 if I_{shape} = 0 (I_{shape} is read from Table 7.2)
or
$Factor_{slight}$ = minimum of (1, K_{shape}) if I_{shape} = 1

New median [moderate] = Old median [for moderate] * (K_{skew}) * (K_{3D})

New median [extensive] = Old median [for extensive] * (K_{skew}) * (K_{3D})

New median [complete] = Old median [for complete] * (K_{skew}) * (K_{3D})

Step 5:
Use the new medians along with the dispersion β = 0.4 to evaluate the ground shaking-related damage state probabilities. Note that Sa(1.0 sec) is the parameter to use in this evaluation.

Step 6:
Evaluate the ground failure-related damage state probabilities. Note that the PGD medians listed in Table 7 will need to be adjusted as follows:

New PGD median [for slight] = ‘Table7.7’ PGD median [for slight] x f_1
New PGD median [moderate] = ‘Table7.7’ PGD median [for moderate] x f_1
New PGD median [extensive] = ‘Table7.7’ PGD median [for extensive] x f_1
New PGD median [complete] = ‘Table7.7’ median [for complete] x f_2

Where f_1 and f_2 are modification factors that are functions of the number of spans (N), width of the span (W), length of the bridge (L), and the skewness (α) and can be computed using the equations in Table 7.8 below.

Table 7.8 Modifiers for PGD Medians

CLASS	f_1	f_2
HWB1	1	1
HWB2	1	1
HWB3	1	1
HWB4	1	1
HWB5	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB6	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB7	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB8	1	sin (α)
HWB9	1	sin (α)
HWB10	1	sin (α)
HWB11	1	sin (α)
HWB12	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB13	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB14	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB15	1	sin (α)
HWB16	1	sin (α)
HWB17	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB18	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB19	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB20	1	sin (α)
HWB21	1	sin (α)
HWB22	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB23	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB24	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB25	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB26	1	sin (α)
HWB27	1	sin (α)
HWB28	1	1

Step 7:

Combine the damage state probabilities and evaluate functionality of bridge.

***Example of bridge damage evaluation*:**
Consider a three-span simply supported prestressed concrete bridge seated on neoprene bearings located in the Memphis area. The table below lists the data for this bridge obtained from NBI. For the scenario earthquake, assume that the ground motion for rock conditions (NEHRP class B) is defined by the following parameters:

Sa(0.3 sec) = 2.1g, Sa(1.0 sec) = 0.24g PGA = 0.38g

Also, assume that the bridge is located in soil type D.

The median spectral acceleration ordinates for different damage states are determined as follows:

First, the ground motion data is amplified for soil conditions (Table 4.10 in Chapter 4):

Sa(0.3 sec) = 2.1g (1 x 2.1g),
Sa(1.0 sec) = 0.43g (1.8 x 0.24g)
PGA = 0.53g (1.4 x 0.38g)

Second, the bridge gets classified.

Bridge data necessary for the analysis

NBI field	Data	Remarks
27	1968	Year built
34	32	Angle of skew
43	501	Prestressed concrete, simple span
45	3	Number of spans
48	23	Maximum span length (m)
49	56	Total bridge length (m)

HAZUS default class for this bridge based on the information above is **HWB17**

Next, the parameters needed in evaluating the median spectral accelerations are computed:

Step 3:

K_{skew} = sqrt[sin(90-α)] =sqrt [sin (90 – 32)] = 0.91

K_{shape} = 2.5 x Sa(1.0 sec) / Sa(0.3 sec) = 0.5

K_{3D} = 1 + A / (N – B) = 1 + 0.25 / (3-1) = 1.125 (See Tables 7.2 and 7.3)

Step 4:

From Table 7.2, I_{shape} is 0 for HWB17, therefore “long periods” governs, and $Factor_{slight}$ is 1. Therefore:

New Sa[1.0 sec] [for slight] = Old Sa[1.0 sec] [for slight] x $Factor_{slight}$
= 0.26g x 1 = 0.26g
New Sa[1.0 sec] [moderate] = Old Sa[1.0 sec] [for moderate] * (K_{skew}) * (K_{3D})
= 0.35g x 0.91 x 1.125 = 0.36g
New Sa[1.0 sec] [extensive] = Old Sa[1.0 sec] [for extensive] * (K_{skew}) * (K_{3D})
= 0.44g x 0.91 x 1.125 = 0.45g
New Sa[1.0 sec] [complete] = Old Sa[1.0 sec] [for complete] * (K_{skew}) * (K_{3D})
= 0.65g x 0.91 x 1.125 = 0.67g

Step 5:
With these new medians, the shaking-related discrete damage state probabilities are (using lognormal functions with the above medians and with betas equal to 0.4):

P[No damage] = 1 – 0.90 = 0.10
P[Slight damage] = 0.90 – 0.67 = 0.23
P[Moderate damage] = 0.67 – 0.46 = 0.21
P[Extensive damage] = 0.46 – 0.13 = 0.33
P[Complete damage] = 0.13

Damage Functions for Tunnels

Tunnel damage functions are based on the damage functions of their subcomponents, namely the liner and the portal (G&E, 1994). G&E findings are based partly on earthquake experience data reported by Dowding et. al. (1978) and Owen et. al (1981). These subcomponent damage functions are given in Tables A.7.1 and A.7.2.

A total of ten tunnel damage functions are obtained, four due to PGA and six due to PGD (i.e., if each class of tunnel is considered separately). Medians and dispersion factors of these damage functions are given in Table 7.9.

Table 7.9 Damage Algorithms for Tunnels (after G&E, 1994)

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Bored/Drilled (HTU1)	slight/minor moderate	0.6 0.8	0.6 0.6
Cut & Cover (HTU2)	slight/minor moderate	0.5 0.7	0.6 0.6

Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
All Tunnels	slight/moderate extensive complete	6.0 12.0 60.0	0.7 0.5 0.5

Graphical representations of these damage functions are also provided. Figures 7.8 and Figure 7.9 plot fragility curves due to PGA for bored/drilled and cut & cover tunnels, respectively, while Figure 7.10 presents fragility curves for tunnels due to PGD.

7.1.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For this level of analysis, the expert can use the methodology developed with the flexibility to (1) include a more refined inventory of the transportation system pertaining to the area of study, and (2) include component-specific and system-specific fragility data. User-supplied damage algorithms can be modified, or replaced, to incorporate improved information about key components of a highway system, such as a major bridge. Similarly, better restoration curves can be developed, given knowledge of available resources and a more accurate layout of the transportation network within the local topographic and geological conditions (i.e., if the redundancy and importance of highway components of the network are known).

7.1.10 References

(1) Applied Technology Council, "Earthquake Damage Evaluation Data for California", ATC-13, Redwood City, CA, 1985.
(2) Dowding, C.H. and Rozen, A., "Damage to Rock Tunnels from Earthquake Shaking", *Journal of the Geotechnical Engineering Division*, American Society of Civil Engineers, New York, NY, February 1978.
(3) National Institute of Building Sciences, “Enhancement of the Highway Transportation Lifeline Module in HAZUS”, prepared by Nesrin Basoz and John Mander, January 1999.
(4) Kim, S.H., "A GIS-Based Regional Risk Analysis Approach for Bridges against Natural Hazards", a dissertation submitted to the faculty of the graduate school of the State University of New York at Buffalo, September 1993.
(5) Owen, G.N. and Scholl, R.E., "Earthquake Engineering Analysis of a Large Underground Structures", Federal Highway Administration and National Science Foundation, FHWA/RD-80/195, January 1981.
(6) G&E Engineering Systems, Inc. (G&E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, Transportation Systems (Highway Systems)", May 1994.

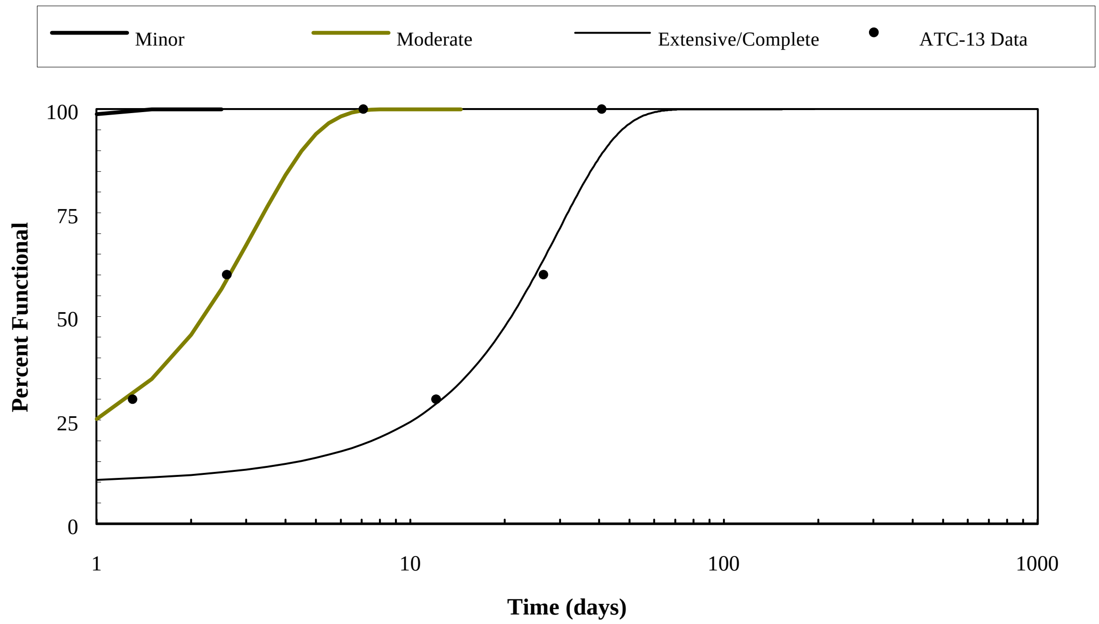


Figure 7.1 Restoration Curves for Urban and Major Roads (after ATC-13, 1985).

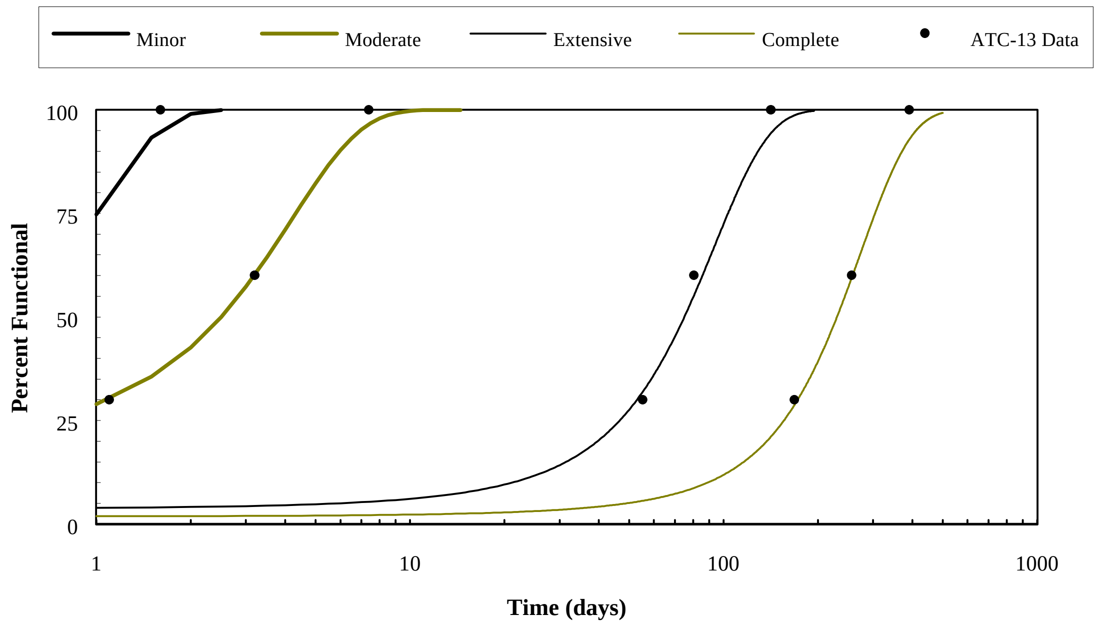


Figure 7.2 Restoration Curves for Highway Bridges (after ATC-13, 1985).

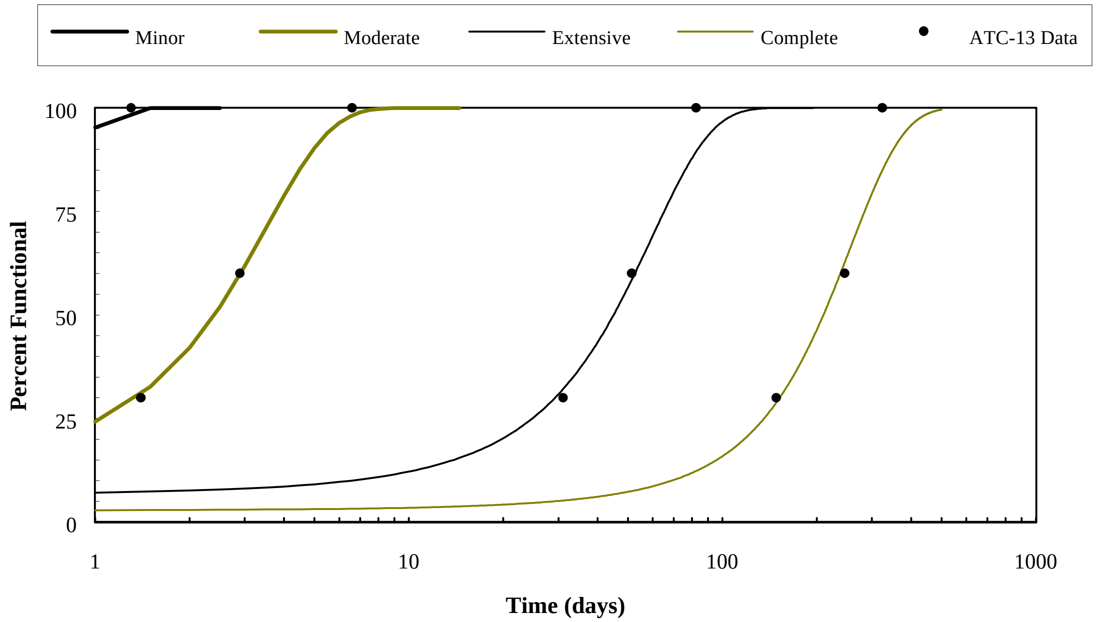


Figure 7.3 Restoration Curves for Highway Tunnels (after ATC-13, 1985).

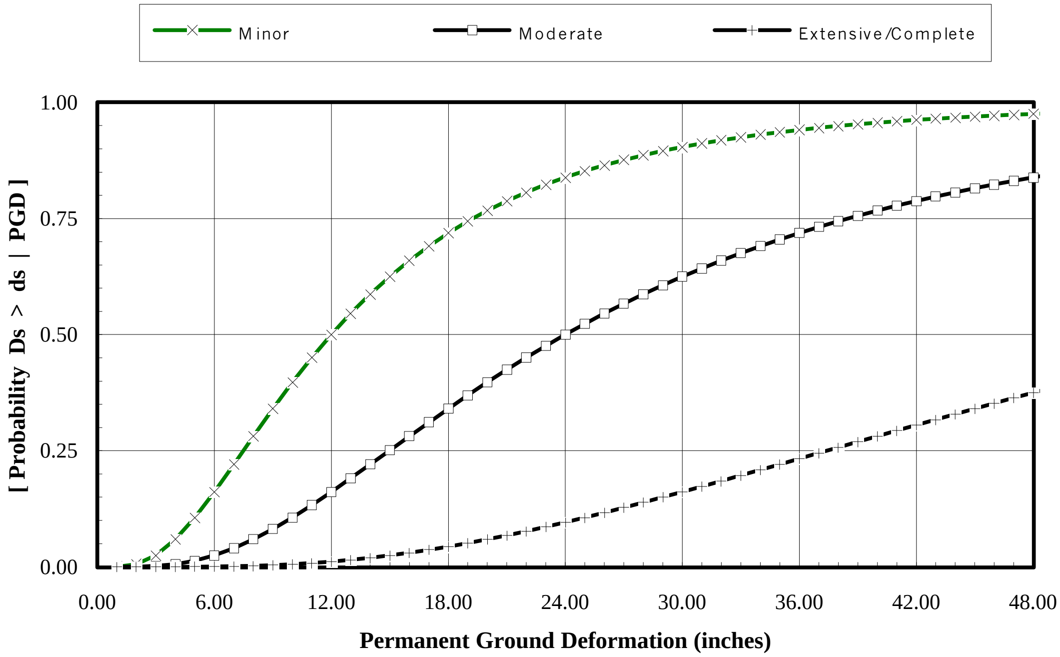


Figure 7.4 Fragility Curves at Various Damage States for Interstate and State Highways.

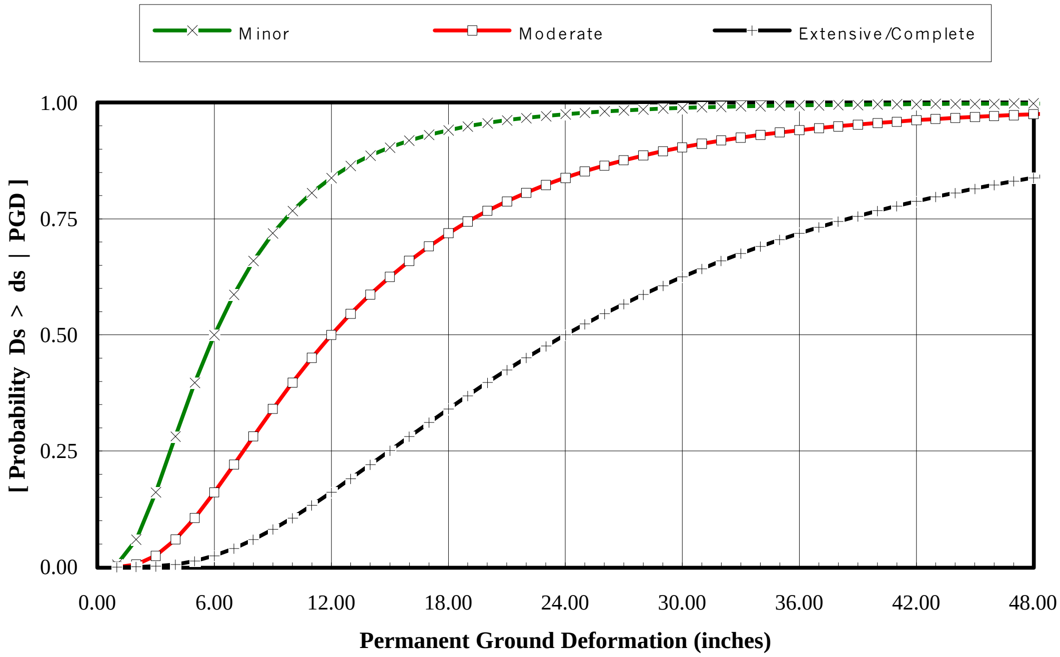


Figure 7.5 Fragility Curves at Various Damage States for Urban roads.

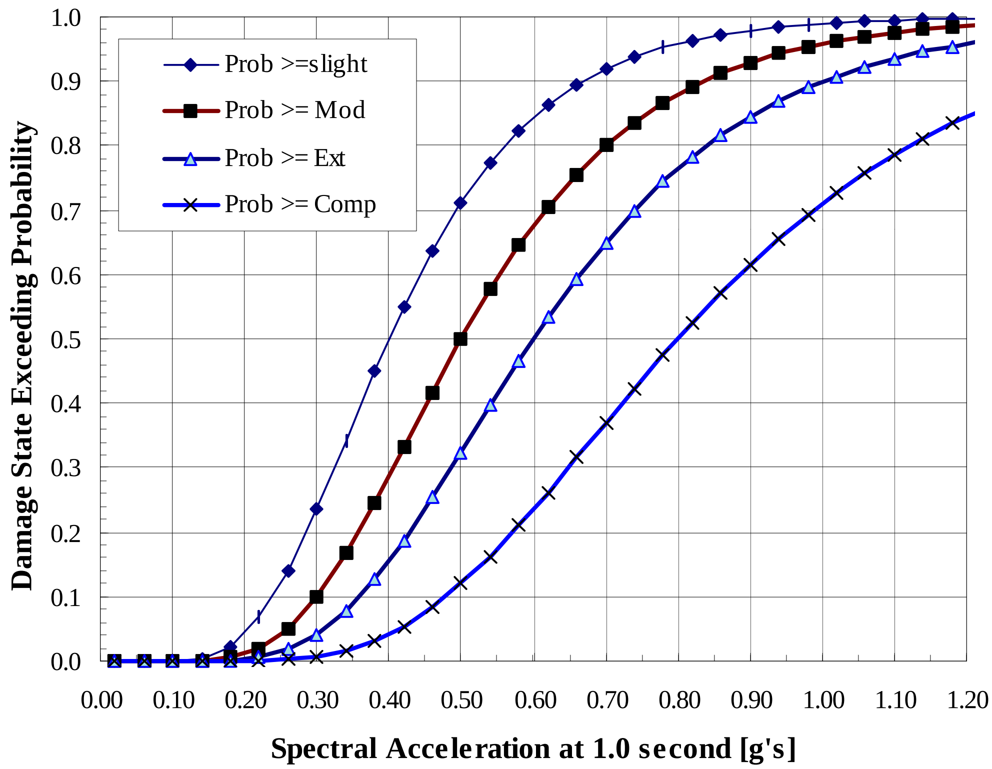


Figure 7.6 Fragility Curves for Conventially Designed Major Bridges (HWB1).

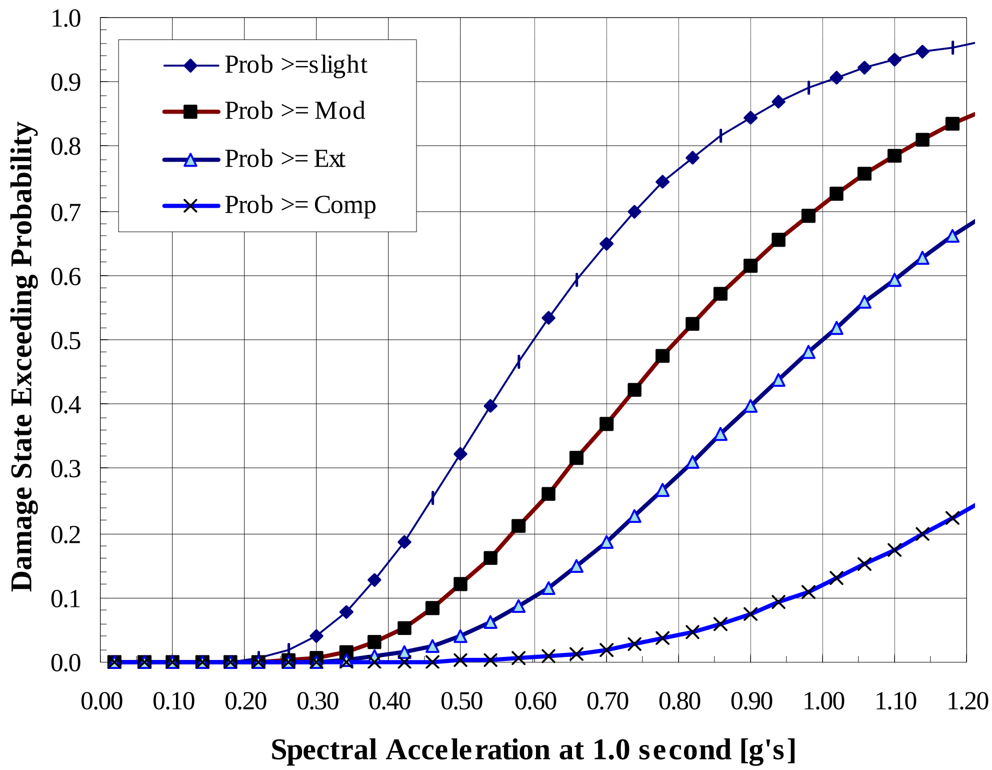


Figure 7.7 Fragility Curves for Seismically Designed Major Bridges (HWB2).

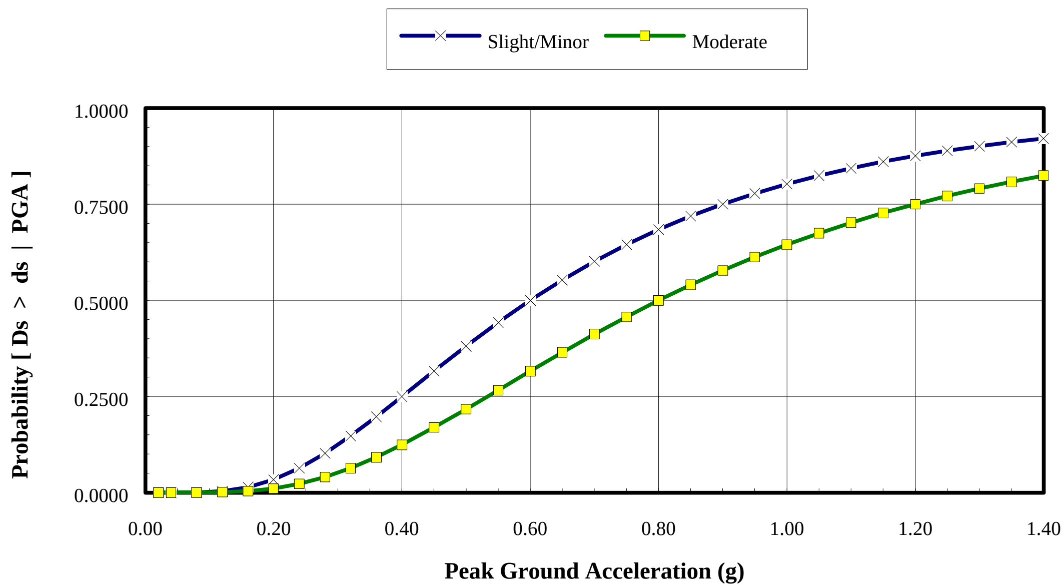


Figure 7.8 Fragility Curves at Various Damage States for Bored/Drilled Tunnels Subject to Peak Ground Acceleration.

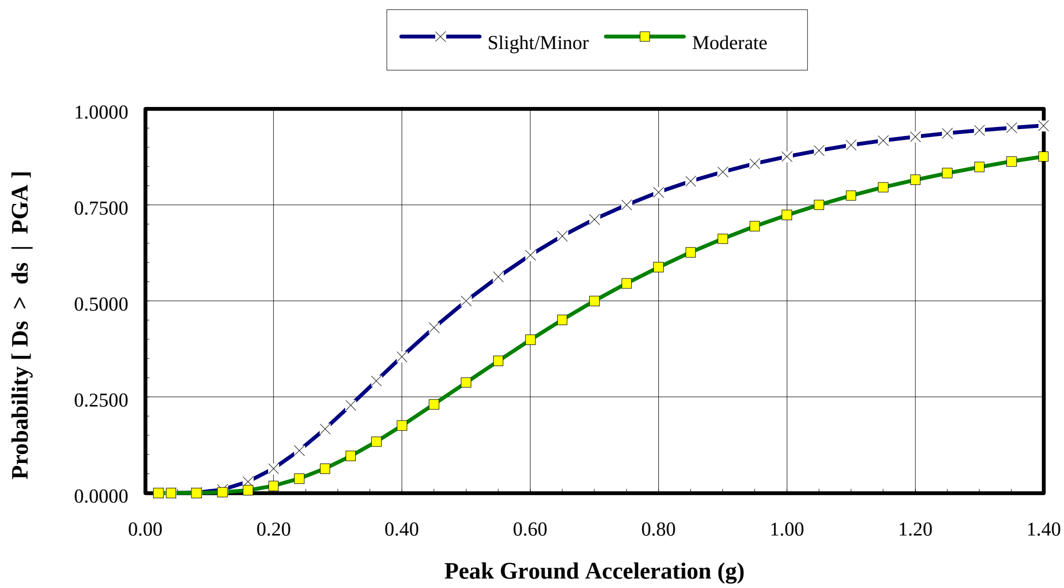


Figure 7.9 Fragility Curves at Various Damage States for Cut & Cover Tunnels Subject to Peak Ground Acceleration.

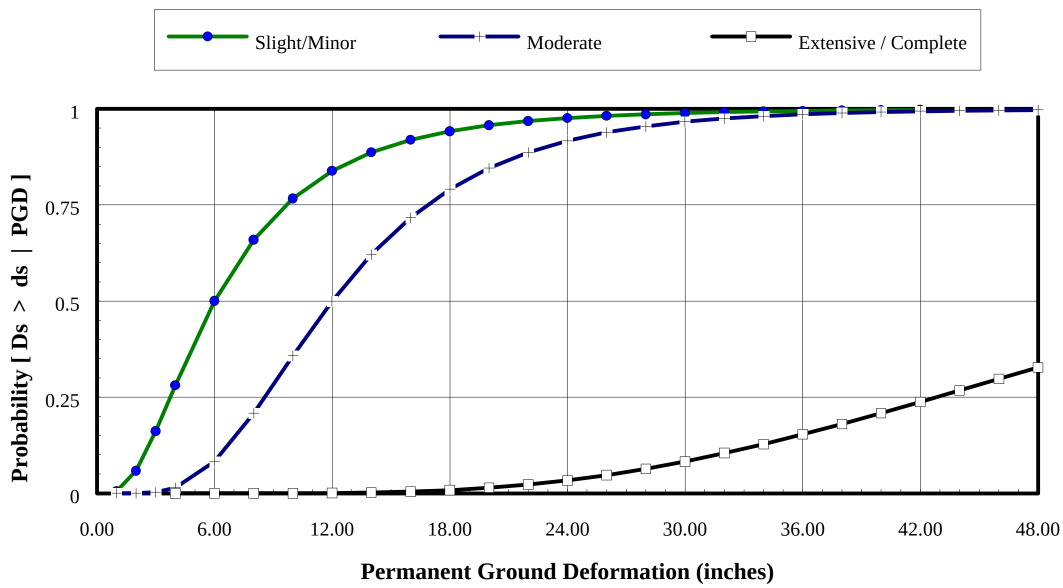


Figure 7.10 Fragility Curves at Various Damage States for All Types of Tunnels Subject to Permanent Ground deformation.

7.2 Railway Transportation System

7.2.1 Introduction

This section presents an earthquake loss estimation methodology for a railway transportation system. This system consists of tracks/roadbeds, bridges, tunnels, urban stations, maintenance facilities, fuel facilities, and dispatch facilities. Past earthquake damage reveals that bridges, tunnels, urban stations, maintenance facilities, fuel facilities, and dispatch facilities are vulnerable to both ground shaking and ground failure, while railway tracks/roadbeds are significantly affected by ground failure alone. Railway tracks located on soft soil or fill or which cross a surface fault rupture can experience failure resulting in loss of functionality. Railway bridges that fail usually result in significant disruption to the transportation network, especially bridges that cross waterways. Likewise, railway tunnels are often not redundant, and major disruption to the transportation system is likely to occur should a tunnel become non-functional.

7.2.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a railway transportation system given knowledge of the system's components (i.e., tracks, bridges, tunnels, stations, maintenance facilities, fuel facilities, or dispatch facilities), the classification of each component (e.g., for fuel facilities, whether the equipment within the facility is anchored or not), and the ground motion (i.e. peak ground acceleration and permanent ground deformation).

Damage states describing the level of damage to each railway system component are defined (i.e. slight/minor, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For example, an extensively damaged railway facility might be closed (0% functional) immediately following the earthquake, but 100% functional after 30 days.

Fragility curves are developed for each type of railway system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion.

Evaluation of component functionality is done similar to the way it was done for highway components.

Interdependence of components on the overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis.

7.2.3 Input Requirements and Output Information

Required input to estimate damage to railway systems includes the following items:

Track and Roadbeds

- Geographical location of railway links [longitude and latitude of end nodes]
- Permanent ground deformation (PGD) at trackbed link

Railway Bridges

- Geographical location of bridge (longitude and latitude)
- Peak ground acceleration (PGA) and PGD at bridge
- Bridge classification

Railway Tunnels

- Geographical location of tunnels (longitude and latitude)
- PGA and PGD at tunnel
- Tunnel classification

Railway System Facilities

- Geographical location of facilities (longitude and latitude)
- PGA and PGD at facility
- Facility classification

Direct damage output for railway systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Damage ratios, used as inputs to the direct economic loss module, are presented in section 15.3 of Chapter 15.

Component functionality is described similar to highway system components, that is, by the probability of being in a damage state (immediately following the earthquake) and by the associated fraction or percentage of the component that is expected to be functional after a specified period of time.

7.2.4 Form of Damage Functions

Damage functions or fragility curves for all railway system components described below are modeled as lognormal functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (PGA) and ground failure is quantified in terms of permanent ground displacement (PGD).

- For tracks/roadbeds, fragility curves are defined in terms of PGD.
- For bridges, fragility curves are defined in terms of PGA and PGD.
- For tunnels, fragility curves are the same as defined for highway systems (in terms of PGA and PGD)
- For railway system facilities, fragility curves are defined in terms of PGA and PGD.

Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the following sections.

7.2.5 Description of Railway System Components

A railway system consists of four components: tracks/roadbeds, bridges, tunnels, and facilities. This section provides a brief description of each.

Tracks/Roadbeds

Tracks/roadbeds refers to the assembly of rails, ties, and fastenings, and the ground on which they rest. Only one classification is adopted for these components. This classification is analogous to that of urban roads in highway systems.

Bridges

Railway bridges are classified as either seismically designed or conventionally designed. These two classifications are analogous to those for bridges in highway systems.

Tunnels

Railway tunnels follow the same classification as highway tunnels. That is, they are classified either as bored/drilled tunnels, or cut & cover tunnels.

Railway System Facilities

Railway system facilities include urban and suburban stations, maintenance facilities, fuel facilities, and dispatch facilities.

Urban and Suburban stations: are generally key connecting hubs that are important for system functionality. In western US, these buildings are mostly made of reinforced concrete shear walls or moment resisting steel frames, while in the eastern US, the small stations are mostly wood and the large ones are mostly masonry or braced steel frames..

Maintenance facilities are housed in large structures that are not usually critical for system functionality as maintenance activities can be delayed or performed elsewhere. These building structures are often made of steel braced frames.

Fuel facilities include buildings, tanks (anchored, unanchored, or buried), backup power systems (if available, anchored or unanchored diesel generators), pumps, and other equipment (anchored or unanchored). It should be mentioned that anchored equipment in general refers to equipment designed with special seismic tiedowns or tiebacks, while unanchored equipment refers to equipment designed with no special considerations other than the manufacturer's normal requirements. While some vibrating components, such as pumps, are bolted down regardless of concern for earthquakes, as used here “anchored” means all components have been engineered to meet seismic criteria which may include bracing (e.g., pipe or stack bracing) or flexibility requirements (e.g., flexible connections across separation joints) as well as anchorage. These definitions of anchored and unanchored apply to all lifeline components. The fuel facility functionality is determined with a fault tree analysis considering redundancies and subcomponent behavior. Note that generic building damage functions are used in this fault tree analysis for developing the overall fragility curve of fuel facilities. Above ground tanks are typically made of steel with roofs also made of steel. Buried tanks are typically concrete wall construction with concrete roofs. In total, five types of fuel facilities are considered. These are: fuel facilities with or without anchored equipment and with or without backup power (all combinations), and fuel facilities with buried tanks.

Dispatch facilities consist of buildings, backup power supplies (if available, anchored or unanchored diesel generators), and electrical equipment (anchored or unanchored). Generic reinforced concrete building with shear walls damage functions, are used in this fault tree analysis for developing the overall fragility curves for dispatch facilities. In total, four types of dispatch facilities are considered. These are dispatch facilities with or without anchored equipment and with or without backup power (all combinations).

7.2.6 Definitions of Damage States

A total of five damage states are defined for railway system components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

Slight/Minor Damage (ds_2)

- For tracks and roadbeds, ds_2 is defined by minor (localized) derailment due to slight differential settlement of embankment or offset of the ground.

- For railway bridges, ds_2 is defined similar to highway bridges.

- For railway tunnels, ds_2 is defined similar to highway tunnels.

- For railway system facilities,

  ◊ for urban stations and maintenance facilities, ds_2 is defined by slight building damage (check building module for full description of potential damage).

  ◊ for fuel facilities with anchored equipment, ds_2 is defined by slight damage to pump building, minor damage to anchor of tanks, or loss of off-site power (check electric power systems for more on this) for a very short period and minor damage to backup power (i.e. to diesel generators, if available).

  ◊ for fuel facilities with unanchored equipment, ds_2 is defined by elephant foot buckling of tanks with no leakage or loss of contents, slight damage to pump building, or loss of commercial power for a very short period and minor damage to backup power (i.e to diesel generators, if available).

  ◊ for fuel facilities with buried tanks (PGD related damage), ds_2 is defined by minor uplift (few inches) of the buried tanks or minor cracking of concrete walls.

  ◊ for dispatch facilities with anchored equipment, ds_2 is defined by minor anchor damage, slight damage to building, or loss of commercial power for a very short period and minor damage to backup power (i.e. diesel generators, if available).

  ◊ for dispatch facilities with unanchored equipment, ds_2 is defined by loss of off-site power for a very short period and minor damage to backup power (i.e. to diesel generators, if available), or slight damage to building.

Moderate Damage (ds_3)

- For railway tracks and roadbeds, ds_3 is defined by considerable derailment due to differential settlement or offset of the ground. Rail repair is required.

- For railway bridges, ds_3 is defined as for highway bridges.

- For railway tunnels, ds_3 is defined as for highway tunnels

- For railway system facilities,

  ◊ for urban stations and maintenance facilities, ds_3 is defined by moderate building damage (check building module for description of potential damage).

  ◊ for fuel facilities with anchored equipment, ds_3 is defined by elephant foot buckling of tanks with no leakage or loss of contents, considerable damage to equipment, moderate damage to pump building, or loss of commercial power for few days and malfunction of backup power (i.e., diesel generators, if available).

◊ for fuel facilities with unanchored equipment, ds_3 is defined by elephant foot buckling of tanks with partial loss of contents, moderate damage to pump building, loss of commercial power for few days and malfunction of backup power (i.e., diesel generators, if available).

◊ for fuel facilities with buried tanks, ds_3 is defined by damage to roof supporting columns, and considerable cracking of walls.

◊ for dispatch facilities with anchored equipment, ds_3 is defined by considerable anchor damage, moderate damage to building, or loss of commercial power for few days and malfunction of backup power (i.e., diesel generators, if available).

◊ for dispatch facilities with unanchored equipment, ds_3 is defined by moderate damage to building, or loss of off-site power for few days and malfunction of backup power (i.e., diesel generators, if available)..

Extensive Damage (ds_4)

- For railway tracks/roadbeds, ds_4 is defined by major differential settlement of the ground resulting in potential derailment over extended length.

- For railway bridges, ds_4 is defined as for highway bridges.

- For railway tunnels, ds_4 is defined as for highway tunnels.

- For railway system facilities,

◊ for urban stations and maintenance facilities, ds_4 is defined by extensive building damage (check building module for description of potential damage).

◊ for fuel facilities with anchored equipment, ds_4 is defined by elephant foot buckling of tanks with loss of contents, extensive damage to pumps (cracked/sheared shafts), or extensive damage to pump building.

◊ for fuel facilities with unanchored equipment, ds_4 is defined by weld failure at base of tank with loss of contents, extensive damage to pump building, or extensive damage to pumps (cracked/sheared shafts).

◊ for fuel facilities with buried tanks, ds_4 is defined by considerable uplift (more than a foot) of the tanks and rupture of the attached piping.

◊ For dispatch facilities with unanchored or anchored equipment, ds_4 is defined by extensive building damage.

<u>Complete Damage</u> (ds_5)

- <u>For railway tracks/roadbeds</u>, ds_5 is the same as ds_4.
- <u>For railway bridges</u>, ds_5 is defined as for highway bridges.
- <u>For railway tunnels</u>, ds_5 is defined as for highway tunnels.
- <u>For railway system facilities</u>,

◊ For urban stations and maintenance facilities, ds_5 is defined by extensive to complete building damage (check building module for description of potential damage).

◊ For fuel facilities with anchored equipment, ds_5 is defined by weld failure at base of tank with loss of contents, or extensive to complete damage to pump building.

◊ For fuel facilities with unanchored equipment, ds_5 is defined by tearing of tank wall or implosion of tank (with total loss of content), or extensive/complete damage to pump building.

◊ For fuel facilities with buried tanks, ds_5 is same as ds_4.

◊ For dispatch facilities with unanchored or anchored equipment, ds_5 is defined by complete damage to building.

7.2.7 Component Restoration Curves

Restoration curves are developed based in part on ATC-13 damage data for the social function classifications of interest (SF 26a through SF 26d) consistent with damage states defined in the previous section. Normally distributed functions are used to approximate these restoration curves, as was done for highway systems. Means and dispersions (standard deviations) of these restoration functions are given in Table 7.10.a. Table 7.10.b gives approximate discrete functions for these developed restoration functions. Figures 7.11 through 7.14 show restoration functions for railway tracks/roadbed, bridges, tunnels and facilities, respectively. ATC-13 restoration data for railway terminal stations are used to generically represent all other railway facilities.

Table 7.10.a Continuous Restoration Functions for Railway System Components (after ATC-13, 1985)

Classification	Damage State	**Mean** (Days)	σ (days)
Railway Tracks	slight/minor	0.9	0.07
	moderate	3.3	3.0
	extensive	15.0	13.0
	complete	65.0	45.0
Railway Bridges	slight/minor	0.9	0.06
	moderate	2.8	1.8
	extensive	31.0	22.0
	complete	110.0	73.0
Railway Tunnels	slight/minor	0.9	0.05
	moderate	4.0	3.0
	extensive	37.0	30.0
	complete	150.0	80.0
Railway Facilities	slight/minor	0.9	0.05
	moderate	1.5	1.5
	extensive	15.0	15.0
	complete	65.0	50.0

Table 7.10.b Discretized Restoration Functions for Railway System Components

Classification	Damage State	1 day	3 days	7 days	30 days	90 days
		Functional Percentage				
Railway Tracks	slight/minor	90	100	100	100	100
	moderate	22	46	90	100	100
	extensive	14	18	28	87	100
	complete	6	8	10	22	70
Railway Bridges	slight/minor	80	100	100	100	100
	moderate	15	55	100	100	100
	extensive	9	10	14	50	100
	complete	7	7	8	14	40
Railway Tunnels	slight/minor	95	100	100	100	100
	moderate	16	38	85	100	100
	extensive	11	13	16	40	97
	complete	3	4	4	7	22
Railway Facilities	slight/minor	95	100	100	100	100
	moderate	37	85	100	100	100
	extensive	15	20	29	83	100
	complete	10	11	12	25	70

7.2.8 Development of Damage Functions

Fragility curves for railway system components are defined with respect to classification and ground motion parameter.

Damage functions for Railway Tracks/Roadbeds

Damage functions for tracks/roadbeds are similar to those of major roads. The medians and dispersions of these curves were given in Table 7.6 (see highway system section).

Damage Functions for Railway Bridges

Fragility curves for the two types of bridges considered herein (seismically designed and conventionally designed) are developed based on the type of damage incurred by the bridge subcomponents. Railway bridges built prior to 1960 should be classified as conventionally designed, while the rest should be classified as seismically designed. Bridge subcomponents include structural elements or portions of the bridge, such as columns, abutments, decks, approaches and connections. Medians and dispersions of damage functions to these subcomponents are summarized in Tables B.7.1 and B.7.2 of Appendix 7B, which correspond to seismically designed and conventionally designed bridges, respectively.

Component fragility curves for railway bridges are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationship between subcomponents. A lognormal curve that best fits the resulting probability distribution is then determined numerically.

A total of sixteen bridge damage functions are obtained, eight are related to PGA while the other eight are PGD related. Half of these damage functions correspond to seismically designed bridges, while the other half correspond to conventionally designed bridges. Medians and dispersions of these damage functions are given in Tables 7.11.a and 7.11.b.

Table 7.11.a Damage Algorithms for Seismically-Designed Railway Bridges

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
All Bridges	slight/minor	0.32	0.45
	moderate	0.62	0.55
	extensive	0.79	0.60
	complete	1.40	0.70

Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
All Bridges	slight/minor	2.0	0.50
	moderate	9.0	0.55
	extensive	11.0	0.55
	complete	15.0	0.55

Table 7.11.b Damage Algorithms for Conventionally-Designed Railway Bridges

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
All Bridges	slight/minor	0.22	0.45
	moderate	0.51	0.55
	extensive	0.60	0.60
	complete	1.00	0.70

Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
All Bridges	slight/minor	2.0	0.50
	moderate	7.0	0.55
	extensive	9.0	0.55
	complete	12.0	0.55

Graphical representations of these damage functions are also provided. Figures 7.15 and 7.16 represent PGA related fragility curves, while Figures 7.17 and 7.18 correspond to PGD related fragility curves.

Damage Functions for Tunnels

Tunnel damage functions are the same as those derived for highways. These were given in Table 7.9 and plotted in Figures 7.9 and 7.10 of the "highway systems" section.

Damage Functions for Railway System Facilities

Damage functions for railway system facilities are defined in terms of PGA and PGD. Note that, unless it is specified otherwise, ground failure (PGD) related damage functions for these facilities are assumed to be similar to those described for buildings. These are:

- For lateral spreading, a lognormal damage function with a median of 60 inches and a dispersion of 1.2 is assumed for the damage state of "at least extensive". 20% of this damage is assumed to be complete. That is, for a PGD of 10" due to lateral spreading, there is a 7% probability of "at least extensive" damage.

- For vertical settlement, a lognormal curve with a median of 10 inches and a dispersion of 1.2 is assumed for the damage state of "at least extensive". 20% of this damage is assumed to be complete. That is, for a PGD of 10" due to vertical settlement, there is a 50% chance of "at least extensive" damage.

- For fault movement or landslide, a lognormal curve with a median of 10 inches and a dispersion of 0.5 is assumed for "complete" damage state. That is, for 10 inches of PGD due to fault movement or landslide, there is a 50% chance of "complete" damage.

An example of how to combine multiple PGD algorithms with a PGA algorithm is presented later in this section.

PGA Damage Functions for Urban Stations and Maintenance Facilities

PGA related damage functions presented in Table 7.12.a are based on the building fragility curves developed in Chapter 5. Note that Table 7.12.a may contain more classes for urban stations or maintenance facilities than there actually are in a given system. Since no default inventory exists for both these two components, the user is expected to specify the appropriate mapping between these facilities and their actual model building types.

Table 7.12.a Damage Algorithms for Urban Stations and Maintenance Facilities

Peak Ground Acceleration					
		Map Area 7	Map Areas 5/6	Map Areas 1-4	For All Areas
Classification	**Damage State**	**Median (in)**	**Median (in)**	**Median (in)**	**β**
RC Shear Wall - low rise (C2L)	slight/minor	0.26	0.19	0.14	0.65
	moderate	0.49	0.35	0.23	0.65
	extensive	0.95	0.69	0.41	0.65
	complete	1.54	1.12	0.64	0.65
Steel Braced Frame - low rise (S2L)	slight/minor	0.24	0.18	0.12	0.65
	moderate	0.48	0.33	0.22	0.65
	extensive	1.05	0.77	0.44	0.65
	complete	1.78	1.3	0.71	0.65
Moment Resisting Steel Frame - low rise (S1L)	slight/minor	0.13	0.1	0.08	0.65
	moderate	0.33	0.23	0.16	0.65
	extensive	0.77	0.55	0.36	0.65
	complete	1.9	1.36	0.76	0.65
Steel Frame w/ URM Infill Walls - low rise (S5L)	slight/minor	0.12	0.12	0.12	0.65
	moderate	0.16	0.16	0.16	0.65
	extensive	0.29	0.29	0.29	0.65
	complete	0.46	0.46	0.46	0.65
Precast Concrete Tiltup Walls - low rise (PC1)	slight/minor	0.11	0.08	0.07	0.65
	moderate	0.25	0.17	0.11	0.65
	extensive	0.63	0.45	0.31	0.65
	complete	1.07	0.78	0.47	0.65
Concrete Frame Building w/ URM Infill Walls (C3L)	slight/minor	0.11	0.11	0.11	0.65
	moderate	0.14	0.14	0.14	0.65
	extensive	0.26	0.26	0.26	0.65
	complete	0.41	0.41	0.41	0.65
Wood, Light Frame (W1)	slight/minor	0.38	0.3	0.23	0.65
	moderate	0.69	0.49	0.36	0.65
	extensive	1.23	0.9	0.69	0.65
	complete	1.79	1.31	0.98	0.65

Damage Functions for Fuel Facilities

Fragility curves are developed for the five types of fuel facilities mentioned before, namely, fuel facilities with anchored equipment and backup power, fuel facilities with anchored equipment but no backup power, fuel facilities with unanchored equipment and backup power, fuel facilities with unanchored equipment and no backup power, and fuel facilities with buried tanks. Medians and dispersions of damage functions to fuel facility subcomponents are summarized in Tables B.7.3 and B.7.4 of Appendix 7B. A generic building type is used in developing fragility curves for fuel facilities in the specified fault tree logic (see Table B.7.3 of Appendix 7B). Note that the interaction effects, specifically that of the electric power module, are considered in this fault tree logic for the slight/minor and moderate damage states (refer to section

8.5.8 of Chapter 8 for more details on loss of commercial power effects on other lifelines).

Component fragility curves are obtained using the same methodology as used for bridges wherein a lognormal curve that best fits the results of the Boolean combination is determined numerically. It should be mentioned that the Boolean logic is implicitly presented within the definition of a particular damage state.

The fault tree shown in Figure 7.19a presents the Boolean logic for the case of moderate damage to fuel facilities with anchored equipment and backup power, while Figure 7.19b compares the fragility curve resulting from the Boolean combination to the fitted lognormal fragility curve. The dotted line in Figure 7.19 represents the overall fuel facility fragility curve.

The medians and dispersions of the damage functions for anchored and unanchored fuel facilities are shown in Table 7.12.b. These damage functions are also shown as fragility curves in Figures 7.20.a through 7.20e.

Table 7.12.b Damage Algorithms for Fuel Facilities

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Facility with Anchored Components w/ Backup Power	slight/minor	0.23	0.50
	moderate	0.43	0.45
	extensive	0.64	0.60
	complete	1.10	0.60
Facility with Anchored Components w/o Backup Power	slight/minor	0.12	0.55
	moderate	0.27	0.50
	extensive	0.64	0.60
	complete	1.10	0.60
Facility with Unchored Components w/ Backup Power	slight/minor	0.10	0.55
	moderate	0.23	0.50
	extensive	0.48	0.60
	complete	0.80	0.60
Facility with Unchored Components w/o Backup Power	slight/minor	0.09	0.50
	moderate	0.20	0.45
	extensive	0.48	0.60
	complete	0.80	0.60

Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
Fuel facility w/ buried tanks	slight/minor	4	0.5
	moderate	8	0.5
	extensive/ Complete	24	0.5

PGA Related Damage Functions for Dispatch Facilities

As with fuel facilities, the same generic building type is used in developing the PGA related fragility curves for dispatch facilities in the fault tree logic. The medians and dispersions of the PGA related damage functions for anchored and unanchored dispatch facilities are given in Table 7.12.c and plotted in Figures 7.21.a through 7.21.d. Note that the medians and dispersions of the damage functions for dispatch facility subcomponents are summarized in Tables B.7.5 and B.7.6 of Appendix 7B.

Table 7.12.c Damage Algorithms for Dispatch Facilities

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Facility with Anchored Components w/ Backup Power	slight/minor	0.15	0.75
	moderate	0.35	0.65
	extensive	0.8	0.80
	complete	1.50	0.80
Facility with Anchored Components w/o Backup Power	slight/minor	0.12	0.50
	moderate	0.27	0.45
	extensive	0.80	0.80
	complete	1.50	0.80
Facility with Unnchored Components w/ Backup Power	slight/minor	0.13	0.55
	moderate	0.28	0.50
	extensive	0.80	0.80
	complete	1.50	0.80
Facility with Unnchored Components w/o Backup Power	slight/minor	0.11	0.45
	moderate	0.23	0.40
	extensive	0.80	0.80
	complete	1.50	0.80

Note that the values of Table 7.12c indicate that the damage functions of dispatch facilities are mostly dominated by the building behavior.

Multiple Hazards Analysis for Railway System Facilities

In this section, a hypothetical example illustrating the methodology for combining multiple hazards for nodal facilities is presented.

Assume that due to some earthquake, a railway fuel facility with anchored components and backup power is subject to a PGA level of 0.3g, a lateral spreading displacement of 12 inches, a vertical settlement of 3 inches, and a potential landslide displacement of 15 inches. Assume also that the probability of liquefaction is 0.6, and that the probability of landslide is 0.7.

- Due to ground shaking, the following probabilities of exceedence are obtained:

$$P[\,D_s \geq ds_2 \mid PGA = 0.3g\,] = 0.70$$
$$P[\,D_s \geq ds_3 \mid PGA = 0.3g\,] = 0.21$$
$$P[\,D_s \geq ds_4 \mid PGA = 0.3g\,] = 0.10$$
$$P[\,D_s \geq ds_5 \mid PGA = 0.3g\,] = 0.02$$

- Due to vertical settlement, the following probabilities of exceedence are obtained:

$$P[\,D_s \geq ds_2 \mid PGD = 3 \text{ inches}\,] = 0.16$$
$$P[\,D_s \geq ds_3 \mid PGD = 3 \text{ inches}\,] = 0.16$$
$$P[\,D_s \geq ds_4 \mid PGD = 3 \text{ inches}] = 0.16$$
$$P[\,D_s \geq ds_5 \mid PGD = 3 \text{ inches}\,] = 20\% * 0.16 = 0.03$$

- Due to lateral spreading, the following probabilities of exceedence are obtained:

$$P[\,D_s \geq ds_2 \mid PGD = 12 \text{ inches}\,] = 0.09$$
$$P[\,D_s \geq ds_3 \mid PGD = 12 \text{ inches}\,] = 0.09$$
$$P[\,D_s \geq ds_4 \mid PGD = 12 \text{ inches}] = 0.09$$
$$P[\,D_s \geq ds_5 \mid PGD = 12 \text{ inches}\,] = 20\% * 0.09 = 0.02$$

Therefore, for liquefaction, <u>vertical settlement controls</u>

- Due to landslide, the following probabilities of exceedence are obtained:

$$P[\,D_s \geq ds_2 \mid PGD = 15 \text{ inches}\,] = 0.64$$
$$P[\,D_s \geq ds_3 \mid PGD = 15 \text{ inches}\,] = 0.64$$
$$P[\,D_s \geq ds_4 \mid PGD = 15 \text{ inches}] = 0.64$$
$$P[\,D_s \geq ds_5 \mid PGD = 15 \text{ inches}\,] = 0.64$$

Next, we compute the combined probabilities of exceedence (from complete to slight/minor):

$$\begin{aligned}
P[\,D_s \geq ds_5\,] &= 0.02 + 0.6x0.03 + 0.7x0.64 \\
&\quad - 0.02x0.6x0.03 - 0.02x0.7x0.64 - 0.6x0.03x0.7x0.64 \\
&\quad + 0.02x0.6x0.03x0.7x0.64 \\
&= 0.47 \\
P[\,D_s \geq ds_4\,] &= 0.10 + 0.6x0.16 + 0.7x0.64 \\
&\quad - 0.10x0.6x0.16 - 0.10x0.7x0.64 - 0.6x0.16x0.7x0.64 \\
&\quad + 0.10x0.6x0.16x0.7x0.64 \\
&= 0.55 \\
P[\,D_s \geq ds_3\,] &= 0.21 + 0.6x0.16 + 0.7x0.64 \\
&\quad - 0.21x0.6x0.16 - 0.21x0.7x0.64 - 0.6x0.16x0.7x0.64 \\
&\quad + 0.21x0.6x0.16x0.7x0.64 \\
&= 0.61 \\
P[\,D_s \geq ds_2\,] &= 0.70 + 0.6x0.16 + 0.7x0.64
\end{aligned}$$

$$
\begin{aligned}
&- 0.70x0.6x0.16 - 0.16x0.7x0.64 - 0.6x0.16x0.7x0.64 \\
&+ 0.70x0.6x0.16x0.7x0.64 \\
&= 0.85
\end{aligned}
$$

Therefore, the combined discrete damage states probabilities are:

$$
\begin{aligned}
&P[\ D_s\ =\ ds_1\ ] = 1 - 0.85 = 0.15 \\
&P[\ D_s\ =\ ds_2\ ] = 0.85 - 0.61 = 0.24 \\
&P[\ D_s\ =\ ds_3\ ] = 0.61 - 0.55 = 0.06 \\
&P[\ D_s\ =\ ds_4\ ] = 0.55 - 0.47 = 0.08 \\
&P[\ D_s\ =\ ds_5\ ] = 0.47
\end{aligned}
$$

These discrete values will then be used in the evalution of functionality and economic losses.

7.2.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For this advanced level of analysis, the expert can take advantage of the methodology's flexibility to (1) include a more refined inventory of the railway system pertaining to the area of study, and (2) include component-specific and system-specific fragility data. Default User-Supplied Data Analysis damage algorithms can be modified, or replaced, to incorporate improved information about key components of a railway system, such as urban stations. Similarly, better restoration curves can be developed, given knowledge of available resources and a more accurate layout of the railway network within the local topographic and geological conditions (i.e., if the redundancy and importance of railway components of the network are known).

7.2.10 References

Applied Technology Council, "Earthquake Damage Evaluation Data for California", ATC-13, Redwood City, CA, 1985.

G&E Engineering Systems, Inc. (G&E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, Transportation Systems (Railway Systems)", May 1994.

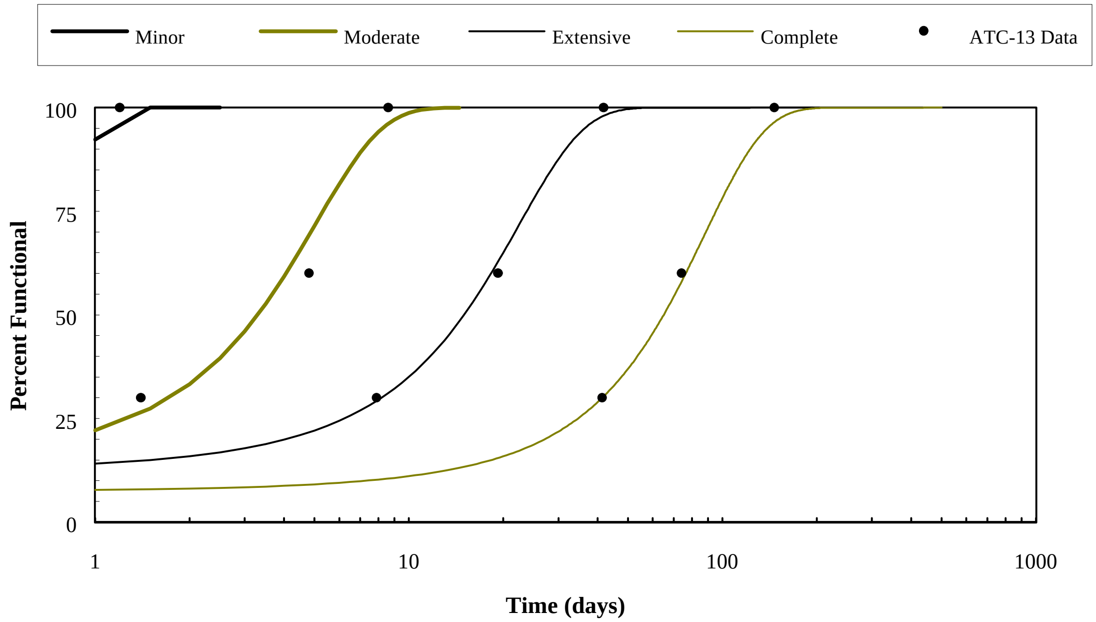


Figure 7.11 Restoration Curves for Railway Tracks/Roadbeds.

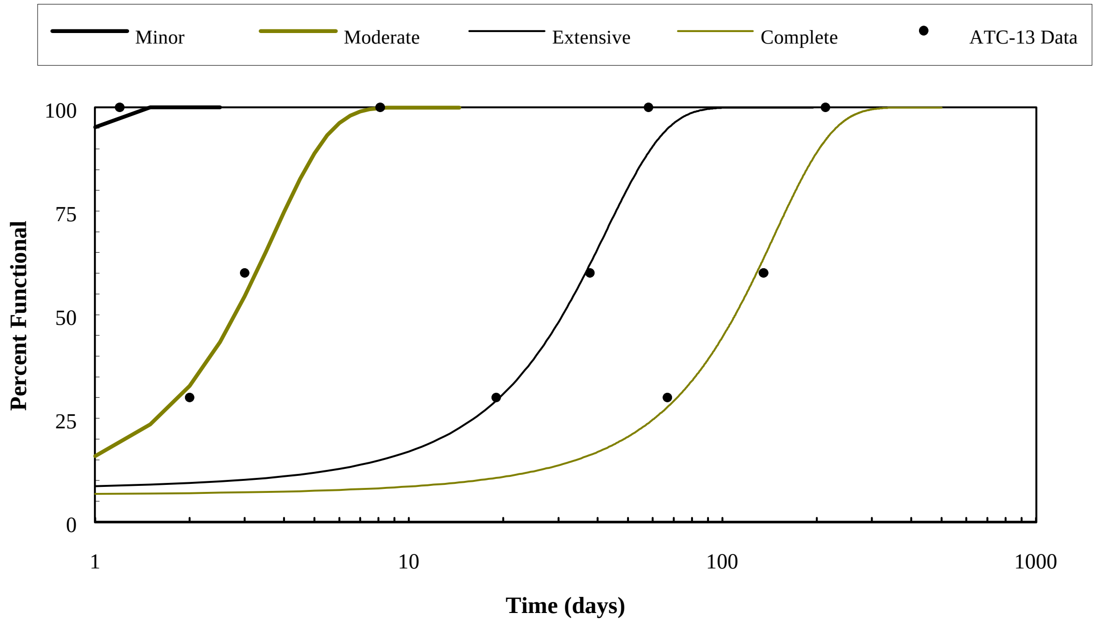


Figure 7.12 Restoration Curves for Railway Bridges.

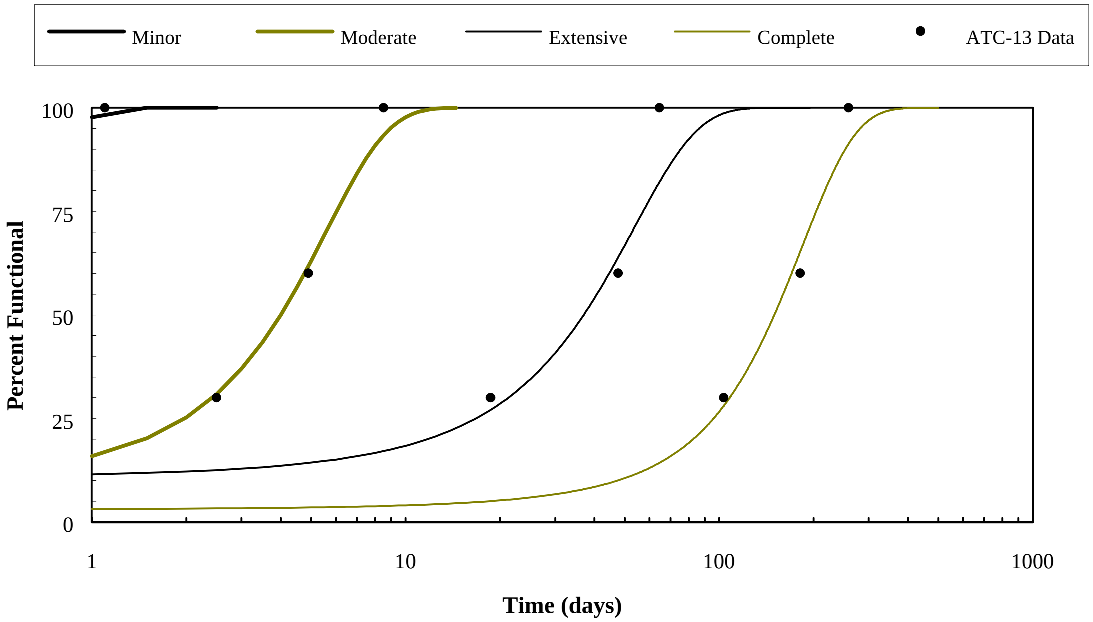


Figure 7.13 Restoration Curves for Railway Tunnels.

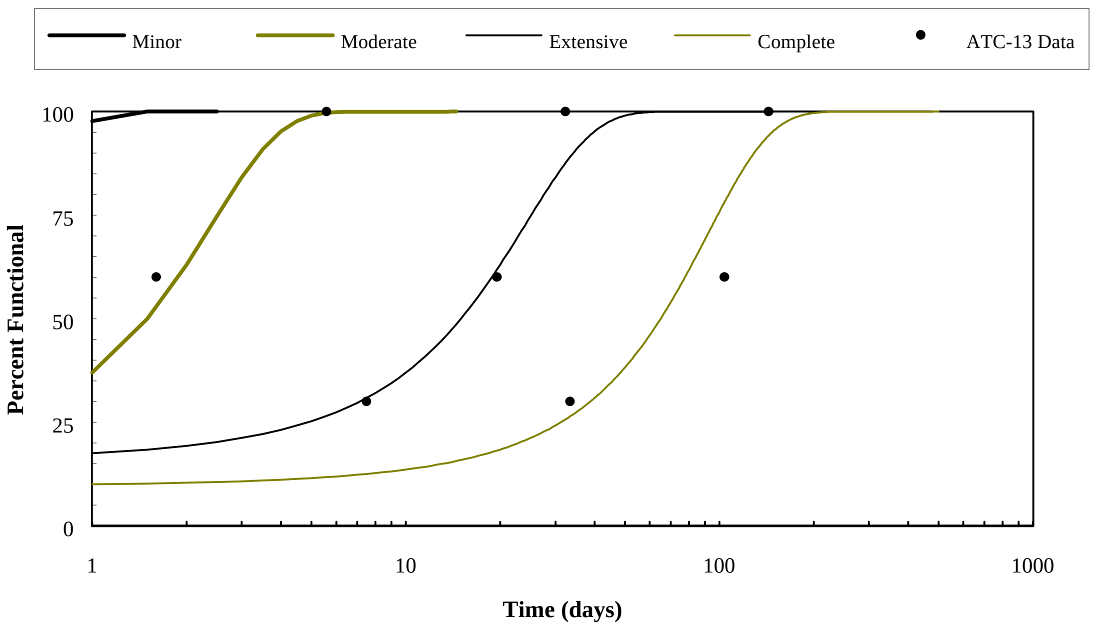


Figure 7.14 Restoration Curves for Railway Facilities.

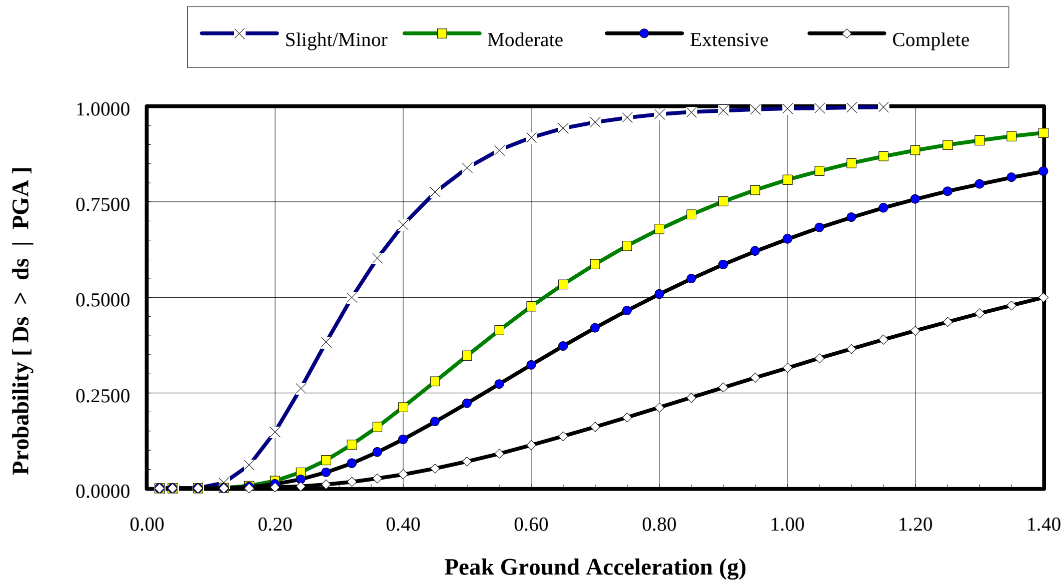


Figure 7.15 Fragility Curves at Various Damage States for Seismically Designed Railway Bridges Subject to Peak Ground Acceleration.

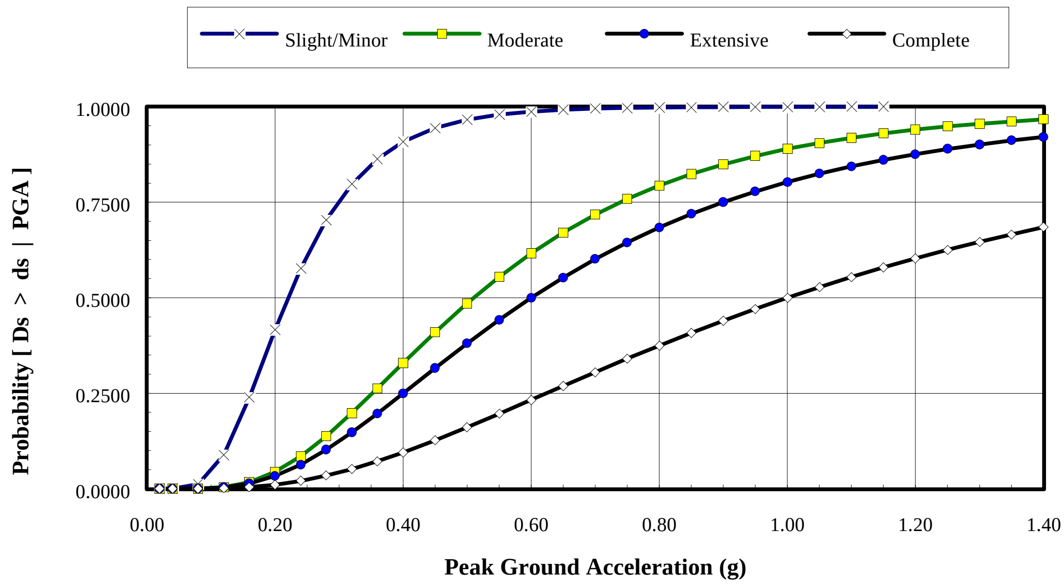


Figure 7.16 Fragility Curves at Various Damage States for Conventionally Designed Railway Bridges Subject to Peak Ground Acceleration.

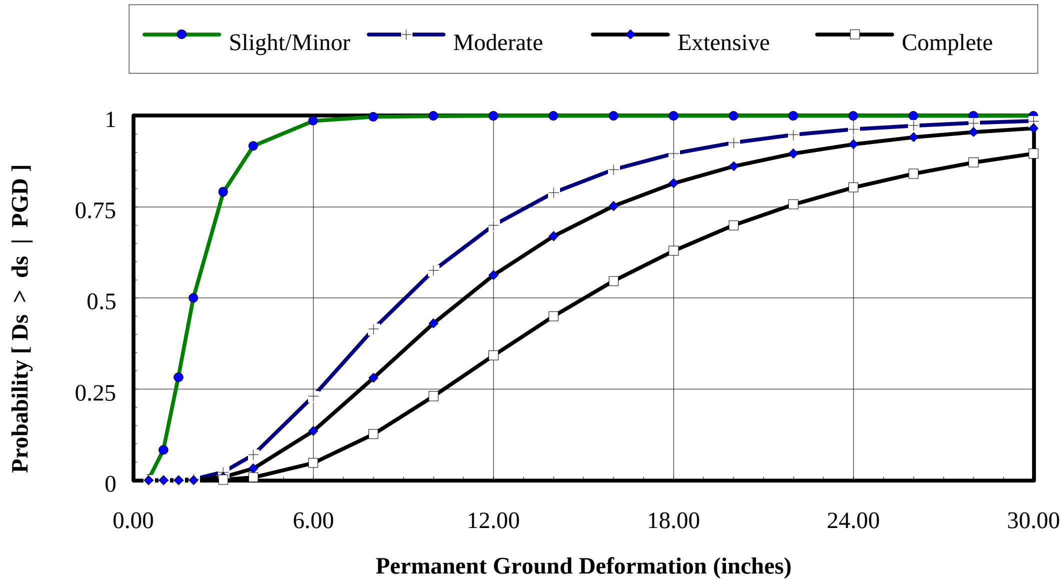


Figure 7.17 Fragility Curves at Various Damage States for Seismically-Designed Railway Bridges Subject to Permanent Ground Deformation.

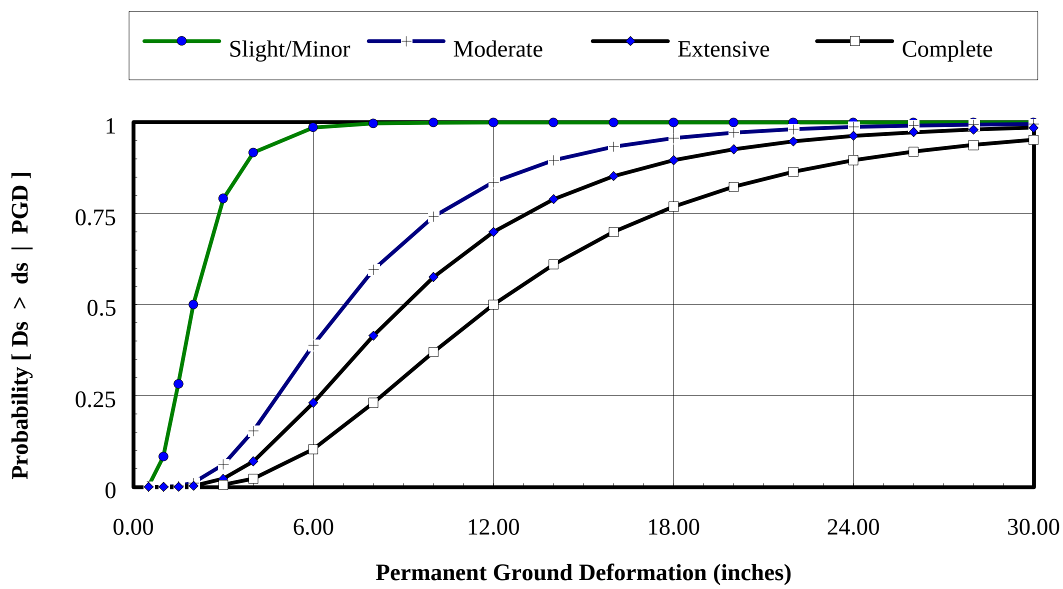


Figure 7.18 Fragility Curves at Various Damage States for Conventionally-Designed Railway Bridges Subject to PGD.

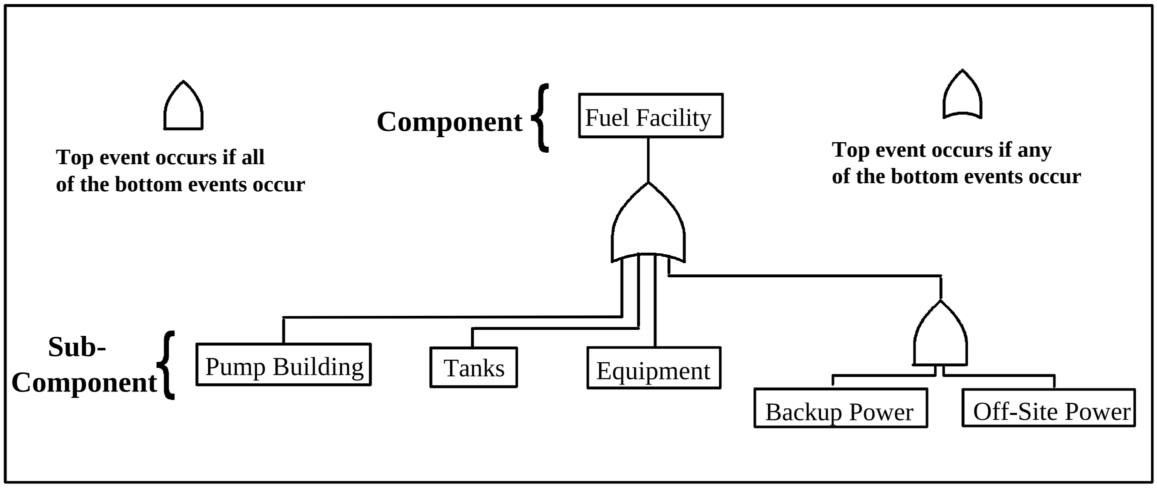


Figure 7.19a Fault Tree for Moderate Damage to Fuel Facilities with Anchored Equipment and Backup Power.

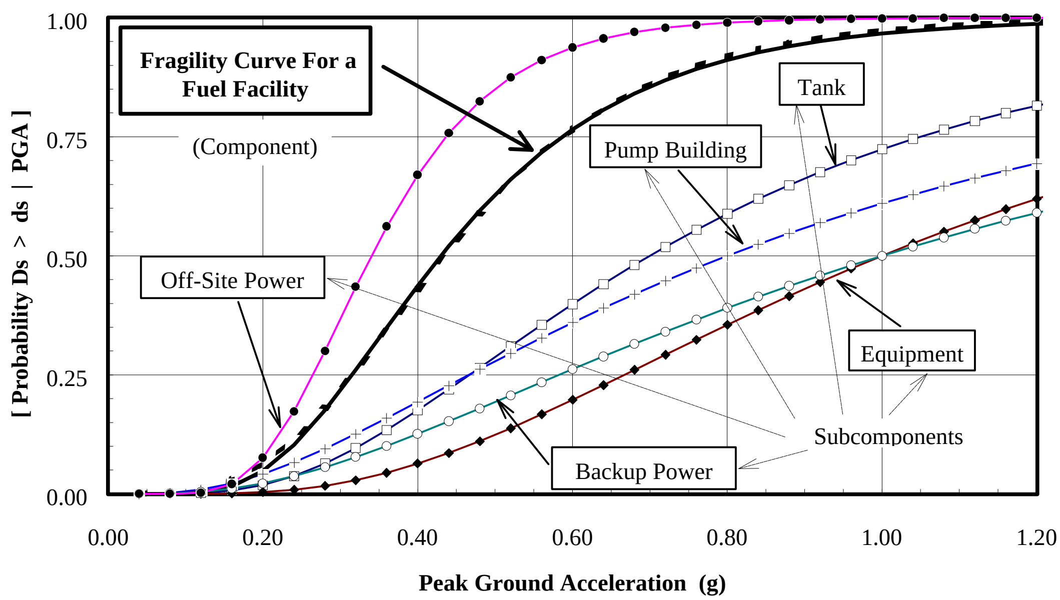


Figure 7.19b An Example of Fitting a Lognormal Curve (solid line) to a Fuel Facility Fragility Curve (dotted line).

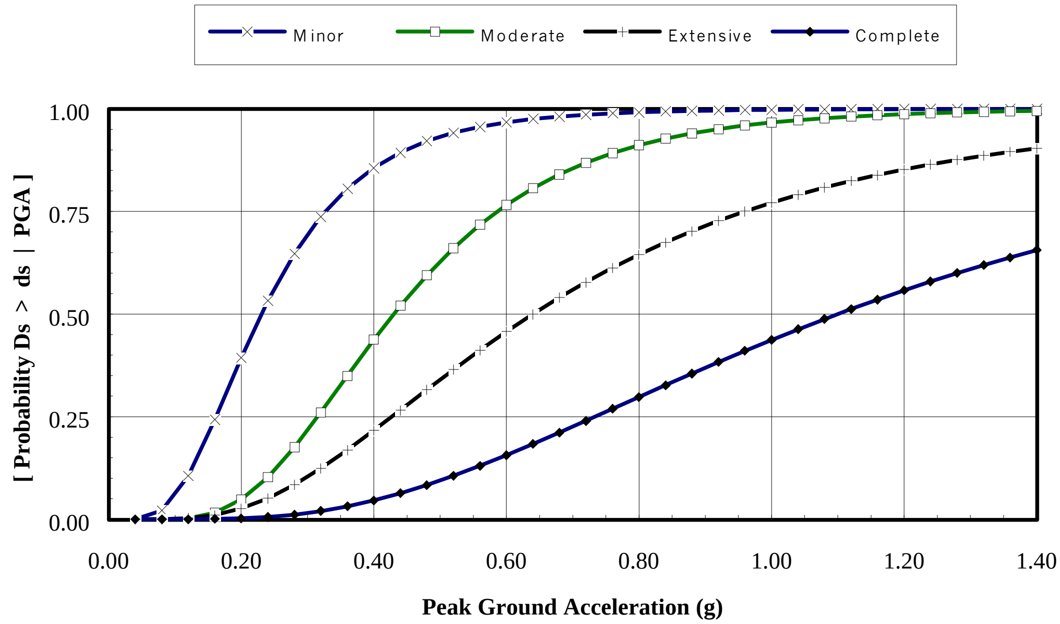


Figure 7.20.a Fragility Curves at Various Damage States for Fuel Facility with Anchored Components and Backup Power.

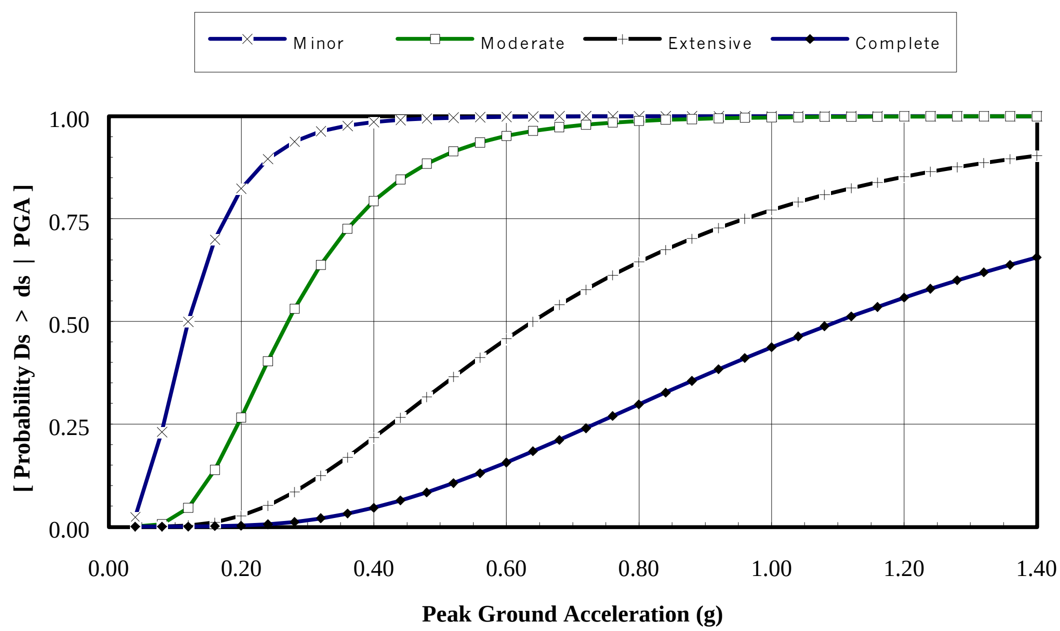


Figure 7.20.b Fragility Curves at Various Damage States for Fuel Facility with Anchored Components but no Backup Power.

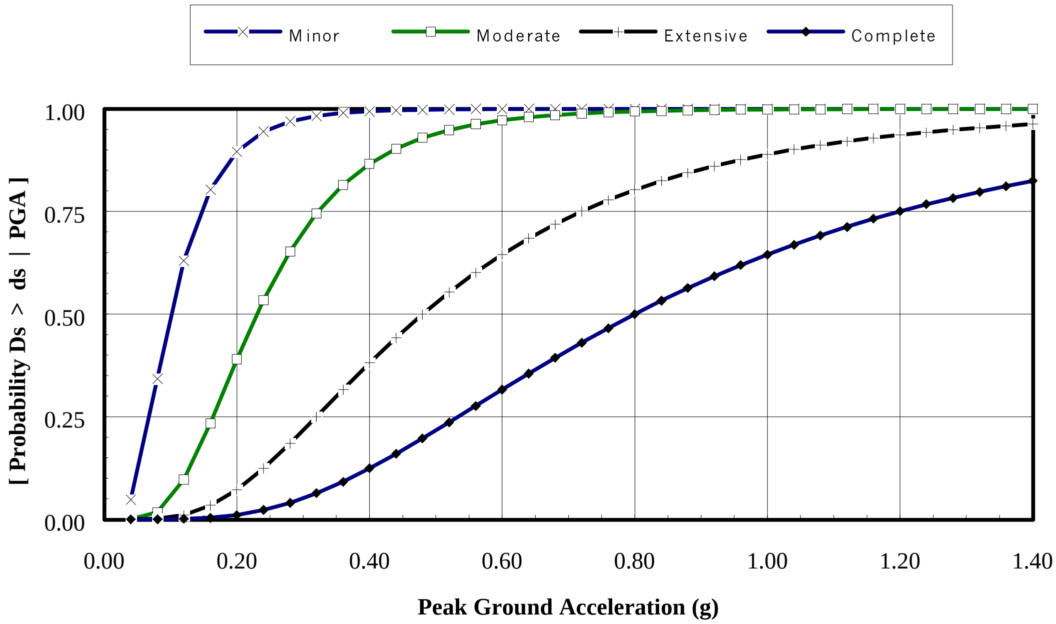


Figure 7.20.c Fragility Curves at Various Damage States for Fuel Facility with Unanchored Components and Backup Power.

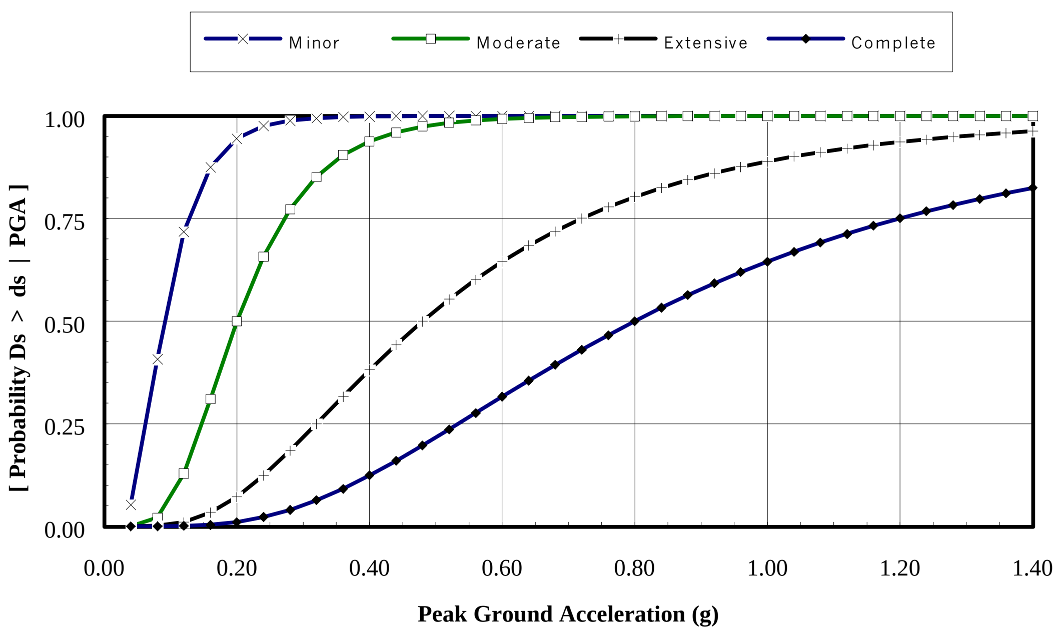


Figure 7.20.d Fragility Curves at Various Damage States for Fuel Facility with Unanchored Components and no Backup Power.

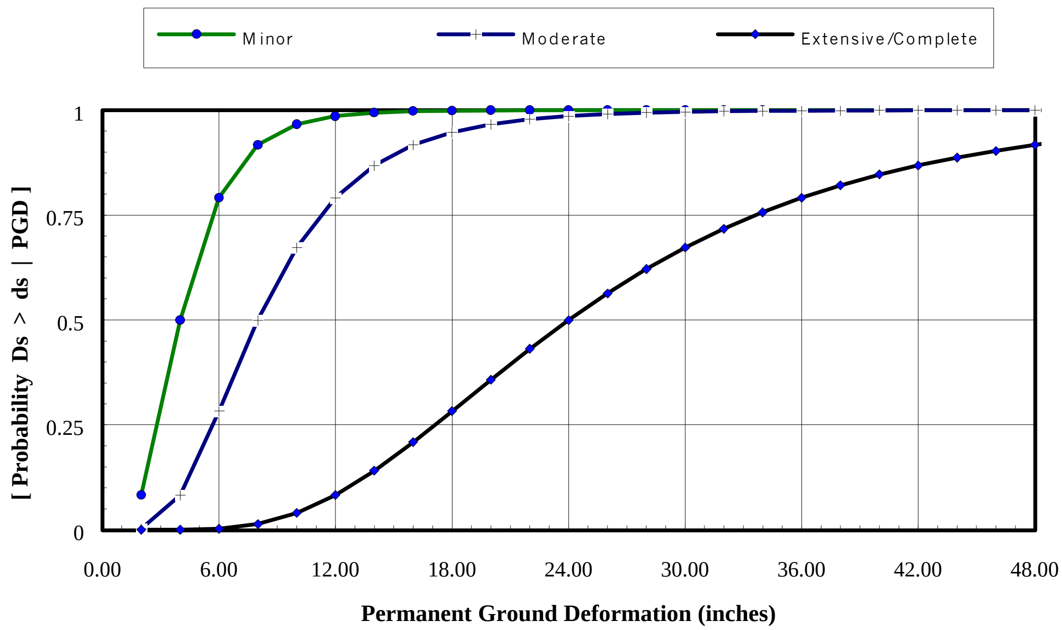


Figure 7.20.e Fragility Curves at Various Damage States for Fuel Facility with Buried Tanks Subject to Permanent Fround Deformation.

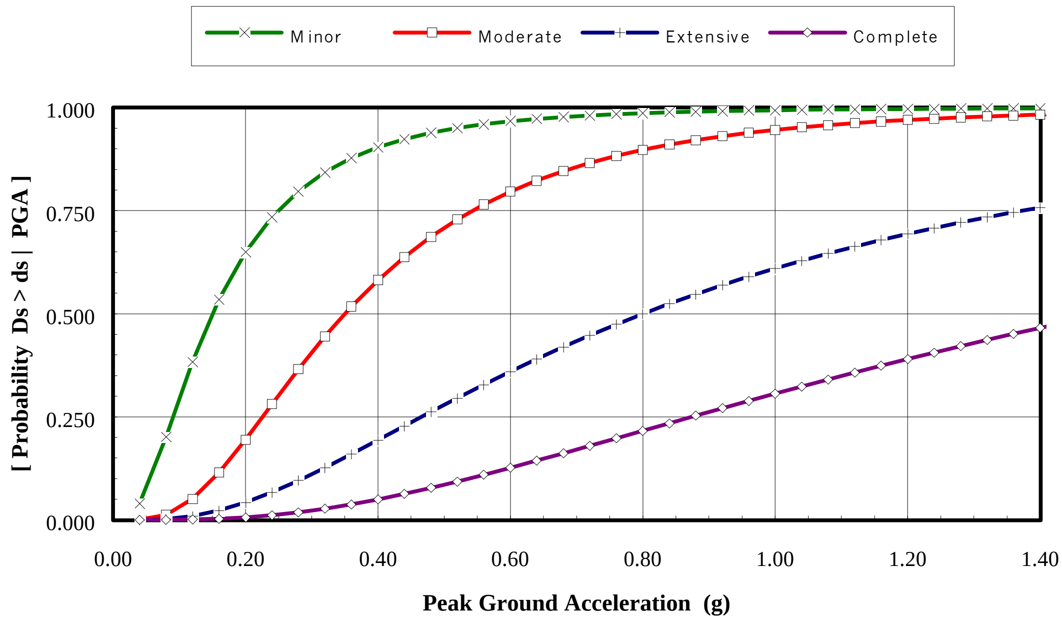


Figure 7.21.a Fragility Curves at Various Damage States for Dispatch Facility with Anchored Components and Backup Power.

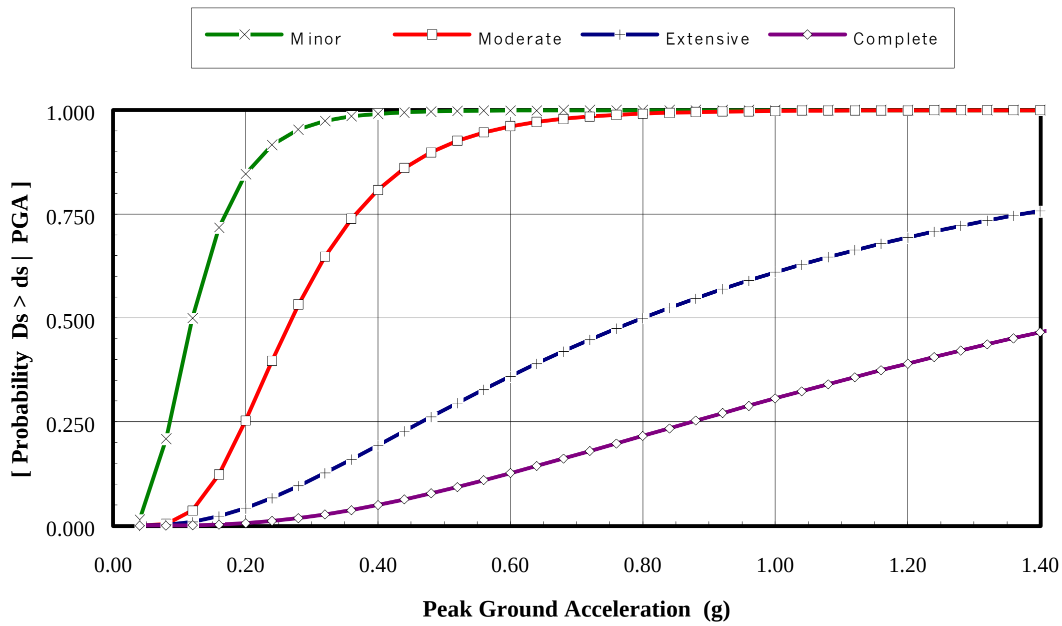


Figure 7.21.b Fragility Curves at Various Damage States for Dispatch Facility with Anchored Components but no Backup Power.

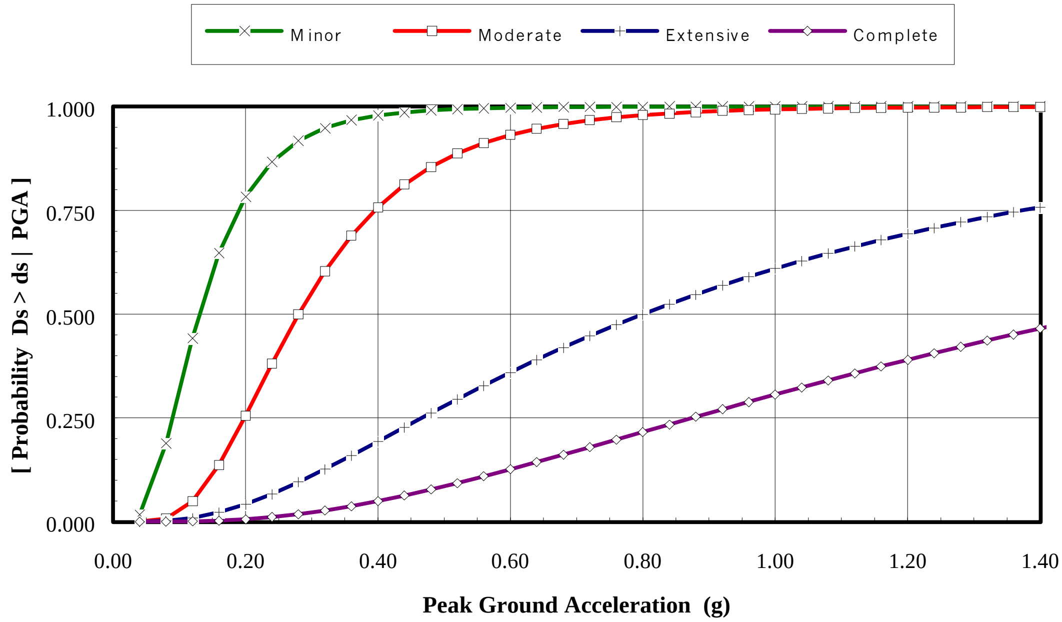


Figure 7.21.c Fragility Curves at Various Damage States for Dispatch Facility with Unanchored Components and Backup Power.

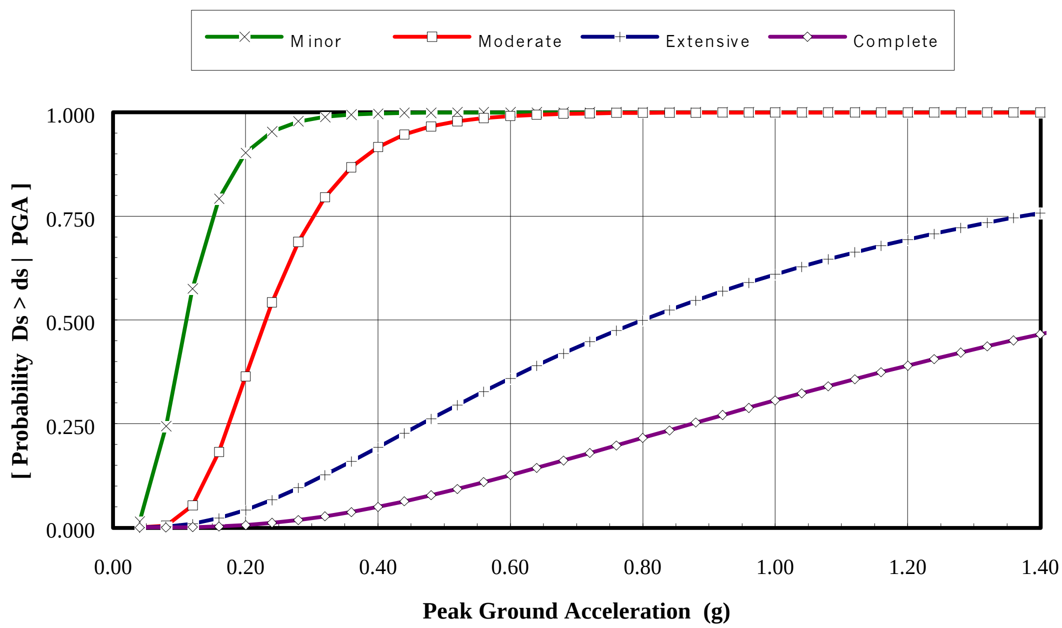


Figure 7.21.d Fragility Curves at Various Damage States for Dispatch Facility with Unanchored Components and no Backup Power.

7.3 Light Rail Transportation System

7.3.1 Introduction

This section presents an earthquake loss estimation methodology for a light rail transportation system. Like railway systems, light rail systems consist of railway tracks/roadbeds, bridges, tunnels, maintenance facilities, dispatch facilities and DC power substations. Therefore, the only difference in the case of light rail systems is in the fuel facilities, which are DC power substations.

7.3.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a light rail transportation system given knowledge of the system's components, the classification of each component (e.g., for dispatch facilities, whether the facility's equipment is anchored or not), and the ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each light rail system component are defined (i.e. slight, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function.

Fragility curves are developed for each type of light rail system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis that would be performed separately by a light rail system expert as an advanced study.

7.3.3 Input Requirements and Output Information

Required input to estimate damage to light rail systems includes the following items:

Light Rail Tracks/Roadbeds

- Geographical location of railway links [longitude and latitude of end nodes]
- Permanent ground deformation (PGD) at roadbed link

Light Rail Bridges

- Geographical location of bridge [longitude and latitude]
- Peak ground acceleration (PGA) and PGD at bridge

- Bridge classification

Light Rail Tunnels

- Geographical location of tunnels [longitude and latitude]
- PGA and PGD at tunnel
- Tunnel Classification

Light Rail Facilities (DC substations, maintenance and dispatch facilities)

- Geographical location of facilities [longitude and latitude]
- PGA and PGD at facility
- Classification

Direct damage output for light rail systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Note that damage ratios, which are the inputs to direct economic loss methods, are described in section 15.3 of Chapter 15.

Component functionality is described by the probability of being in a damage state (immediately following the earthquake) and by the associated fraction or percentage of the component that is expected to be functional after a specified period of time.

7.3.4 Form of Damage Functions

Damage functions or fragility curves for all light rail system components mentioned above are modeled as lognormal functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (PGA) and ground failure is quantified in terms of permanent ground displacement (PGD).

- Fragility curves for tracks/roadbeds are the same as for railway tracks/roadbeds.
- Fragility curves for bridges are the same as for railway bridges.
- Fragility curves for tunnels are the same as for railway tunnels.
- Fragility curves for maintenance and dispatch facilities are the same as for railway maintenance and dispatch facilities.
- Fragility curves for DC power substations are defined in terms of PGA and PGD.

7.3.5 Description of Light Railway System Components

A light rail system consists mainly of six components: tracks/roadbeds, bridges, tunnels, maintenance facilities, dispatch facilities, and DC power substations. The first five are the same as for railway systems and are already described in Section 7.2. Therefore, only DC substations will be described in this subsection.

<u>DC Power Substations</u>

Light rail systems use electric power and have low voltage DC power substations. DC power is used by the light rail system's electrical distribution system. The DC power substations consist of electrical equipment, which convert the local electric utility AC power to DC power. Two types of DC power stations are considered. These are: (1) DC power stations with anchored (seismically designed) components and (2) DC power stations with unanchored (which are not seismically designed) components.

7.3.6 Definitions of Damage States

A total of five damage states are defined for light rail system components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

<u>Slight or Minor Damage</u> (ds_2)

- <u>For tracks/roadbeds</u>, ds_2 is defined similar to railway tracks.
- <u>For light rail bridges</u>, ds_2 is defined similar to railway bridges.
- <u>For light rail tunnels</u>, ds_2 is defined similar to highway tunnels.
- <u>For light rail system facilities</u>,

  ◊ For maintenance facilities, ds_2 is defined similar to railway maintenance facilities.

  ◊ For dispatch facilities, ds_2 is defined similar to railway dispatch facilities.

  ◊ For DC power substations with anchored or unanchored components, ds_2 is defined by loss of off-site power for a very short period, or slight damage to building.

<u>Moderate Damage</u> (ds_3)

- <u>For tracks/roadbeds</u>, ds_3 is defined similar to railway tracks.
- <u>For light rail bridges</u>, ds_3 is defined similar to railway bridges.
- <u>For light rail tunnels</u>, ds_3 is defined similar to highway tunnels.

- For light rail system facilities,

  ◊ For maintenance facilities, ds_3 is defined similar to railway maintenance facilities.

  ◊ For dispatch facilities, ds_3 is defined similar to railway dispatch facilities.

  ◊ For DC power substations with anchored or unanchored components, ds_3 is defined by loss of off-site power for few days, considerable damage to equipment, or moderate damage to building.

Extensive Damage (ds_4)

- For tracks/roadbeds, ds_4 is defined similar to railway tracks.
- For light rail bridges, ds_4 is defined similar to railway bridges.
- For light rail tunnels, ds_4 is defined similar to highway tunnels.
- For light rail system facilities,

  ◊ For maintenance facilities, ds_4 is defined similar to railway maintenance facilities.

  ◊ For dispatch facilities, ds_4 is defined similar to railway dispatch facilities.

  ◊ For DC power substations with anchored or unanchored components, ds_4 is defined by extensive building damage.

Complete Damage (ds_5)

- For tracks/roadbeds, ds_5 is defined similar to railway tracks.
- For light rail bridges, ds_5 is defined similar to railway bridges.
- For light rail tunnels, ds_5 is defined similar to highway tunnels.
- For light rail system facilities,

  ◊ For maintenance facilities, ds_5 is defined similar to railway maintenance facilities.

  ◊ For dispatch facilities, ds_5 is defined similar to railway dispatch facilities.

◊ For DC power substations with anchored or unanchored components, ds_5 is defined by complete building damage.

7.3.7 Component Restoration Curves

The restoration curves for light rail tracks/roadbeds, bridges, tunnels, and facilities are assumed to be the same as those for railway system components.

7.3.8 Development of Damage Functions

Fragility curves for light rail system components are defined with respect to classification and ground motion parameter. Again, except for DC power stations, damage functions of the other light rail system components have been already established in either section 7.1 (highway systems) or section 7.2 (railway systems).

Damage functions for Light Rail Tracks/Roadbeds

See damage functions for railway tracks/roadbeds.

Damage Functions for Light Rail Bridges

See damage functions for railway bridges.

Damage Functions for Light Rail Tunnels

See damage functions for highway tunnels.

Damage Functions for Light Rail System Facilities

Damage functions for light rail system facilities are defined in terms of PGA and PGD. Note that ground failure (PGD) related damage functions for these facilities are assumed to be similar to those described for railway system facilities in section 7.2.8.

PGA Related Damage Functions for Maintenance Facilities

Maintenance facilities for light rail systems are mostly made of steel braced frames. Since no default inventory is provided for these facilities, the user will be expected to provide the appropriate mapping between these facilities whose damage functions are listed in Table 7.7 of section 7.2.8 and their model building types.

PGA Related Damage Functions for Dispatch Facilities

See damage functions for railway dispatch facilities.

PGA Related Damage Functions for DC Power Substations

Fragility curves for the two types of DC power substations are developed based on the type of damage incurred by the DC power substation subcomponents (building, equipment, and off-site power for interaction effects). These two types are DC power substations with unanchored equipment, and DC power substations with unanchored equipment. Medians and dispersions of damage functions to DC power substations subcomponents are summarized in Tables C.7.1 and C.7.2 of Appendix 7C. Component fragility curves are obtained using the same methodology as used before. That is, each fragility curve is determined by a lognormal curve that best fits the results of the Boolean combination. It should be mentioned that the Boolean logic is implicitly presented within the definition of a particular damage state. The medians and dispersions of the damage functions for anchored and unanchored DC power substations are shown in Table 7.13 and plotted in Figures 7.22.a and 7.22.b.

Table 7.13 Damage Algorithms for DC Power Substations

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Substation with Anchored Components	slight moderate extensive complete	0.12 0.27 0.80 1.50	0.55 0.45 0.80 0.80
Substation with Unnchored Components	slight moderate extensive complete	0.11 0.23 0.80 1.50	0.50 0.40 0.80 0.80

7.3.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For this type of analysis, the expert can use the methodology developed with the flexibility to (1) include a refined inventory of the light rail system pertaining to the area of study, and (2) include component specific and system specific fragility data. Default User-Supplied Data Analysis damage algorithms can be modified or replaced to accommodate any specified key component of a light railway system, such as a bridge. Similarly, better restoration curves could be developed given knowledge of available resources and a more accurate layout of the light rail network within the local topographic and geological conditions (i.e. redundancy and importance of a light railway component in the network are known).

7.3.10 References

Applied Technology Council, "Earthquake Damage Evaluation Data for California", ATC-13, Redwood City, CA, 1985.

G & E Engineering Systems, Inc. (G & E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, Transportation Systems", May 1994.

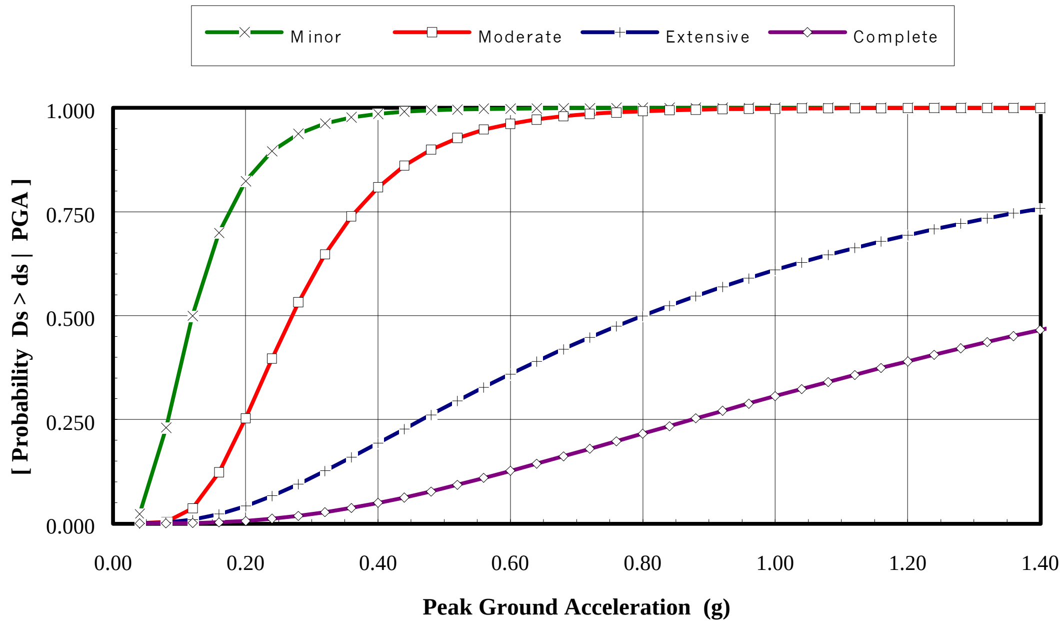


Figure 7.22.a Fragility Curves at Various Damage States for DC Power Substations with Anchored Components.

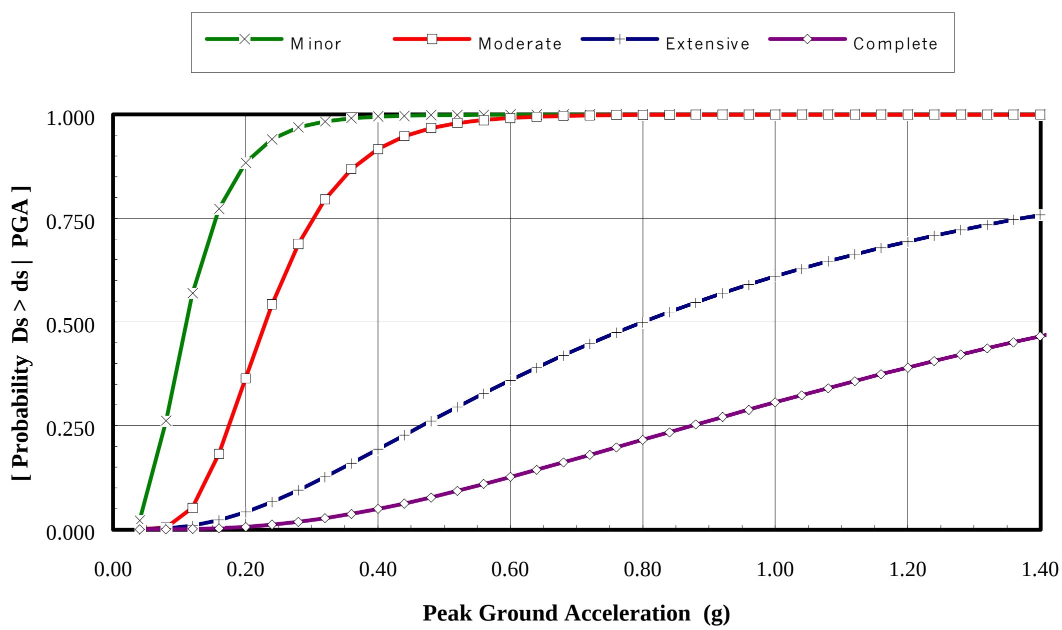


Figure 7.22.b Fragility Curves at Various Damage States for DC Power Substations with Unanchored Components.

7.4 Bus Transportation System

7.4.1 Introduction

This section presents a loss estimation methodology for a bus transportation system during earthquakes. Bus facilities consist of maintenance, fuel, and dispatch facilities. The facilities may sustain damage due to ground shaking or ground failure. Major losses can occur if bus maintenance buildings collapse, and operational problems may arise if a dispatch facility is damaged.

7.4.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a bus transportation system given knowledge of components (i.e., fuel, maintenance, and dispatch facilities with or without backup power), classification (i.e. for fuel facilities, anchored or unanchored components), and the ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each of the bus system components are defined (i.e. slight, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For bus systems, the restoration is dependent upon the extent of damage to the fuel, maintenance, and dispatch facilities.

Fragility curves are developed for each class of bus system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion. Based on these fragility curves, a method for assessing functionality of each of the three bus system components is presented.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis that would be performed separately by a bus system expert as an advanced study.

7.4.3 Input Requirements and Output Information

Required input to estimate damage to bus systems includes the following items:

<u>Urban Stations</u>

- Geographical location of site
- PGA and PGD at station
- Classification

Fuel Facilities

- Geographical location of site
- PGA and PGD at facility
- Classification (i.e. with or without anchored equipment and backup power)

Maintenance Facilities

- Geographical location of site
- PGA and PGD at facility
- Classification (i.e. building type)

Dispatch Facilities

- Geographical location of each warehouse
- PGA and PGD at facility
- Classification (i.e. with or without anchored equipment and backup power)

Direct damage output for bus systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio.

Component functionality is described by the probability of being in a damage state (immediately following the earthquake) and by the associated fraction or percentage of the component that is expected to be functional after a specified period of time.

7.4.4 Form of Damage Functions

Damage functions or fragility curves for all three bus system components, mentioned above, are lognormal functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (PGA) and ground failure is quantified in terms of permanent ground displacement (PGD).

- For urban stations, the fragility curves are defined in terms of PGA and PGD.

- For fuel facilities, the fragility curves are defined in terms of PGA and PGD.

- For maintenance facilities, the fragility curves are defined in terms of PGA and PGD.

- For dispatch facilities, the fragility curves are defined in terms of PGA and PGD.

Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the following section.

7.4.5 Description of Bus System Components

A bus system consists mainly of four components: urban stations, fuel facilities, maintenance facilities, and dispatch facilities. This section provides a brief description of each.

Urban Stations

These are mainly buildings structures.

Bus System Fuel Facilities

Fuel facility consists of fuel storage tanks, buildings, pump equipment and buried pipe, and, sometimes, backup power. The fuel facility functionality is determined with a fault tree analysis considering redundancies and sub-component behavior. The same classes assumed for railway fuel facilities are assumed here. These are listed in Table 3.9.

Bus System Maintenance Facilities

Maintenance facilities for bus systems are mostly made of steel braced frames. The same classes assumed for railway maintenance facilities are assumed here. These are listed in Table 3.9.

Bus System Dispatch Facilities

The same classes assumed for railway dispatch facilities are assumed here. These are listed in Table 3.9.

7.4.6 Definitions of Damage States

A total of five damage states are defined for highway system components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

Slight Damage (ds_2)

◊ For urban stations, ds_2 is defined similar to railway urban stations.

◊ For fuel facilities, ds_2 is defined similar to railway fuel facilities.

◊ For maintenance facilities, ds_2 is defined similar to railway maintenance facilities.

◊ For dispatch facilities, ds_2 is defined similar to railway dispatch facilities.

Moderate Damage (ds_3)

◊ For urban stations, ds_3 is defined similar to railway urban stations.

◊ For fuel facilities, ds_3 is defined similar to railway fuel facilities.

◊ For maintenance facilities, ds_3 is defined similar to railway maintenance facilities.

◊ For dispatch facilities, ds_3 is defined similar to railway dispatch facilities.

Extensive Damage (ds_4)

◊ For urban stations, ds_4 is defined similar to railway urban stations.

◊ For fuel facilities, ds_4 is defined similar to railway fuel facilities.

◊ For maintenance facilities, ds_4 is defined similar to railway maintenance facilities.

◊ For dispatch facilities, ds_4 is defined similar to railway dispatch facilities.

Complete Damage (ds_5)

◊ For urban stations, ds_5 is defined similar to railway urban stations.

◊ For fuel facilities, ds_5 is defined similar to railway fuel facilities.

◊ For maintenance facilities, ds_5 is defined similar to railway maintenance facilities.

◊ For dispatch facilities, ds_5 is defined similar to railway dispatch facilities.

7.4.7 Component Restoration Curves

Restoration Curves are developed based on a best fit to ATC-13 damage data for the social functions SF 26a through SF 26d, consistent with damage states defined in the previous section. Normal distribution functions are developed using the ATC-13 data for the mean time for 30%, 60% and 100% restoration of different sub-components in different damage states. The restoration curves for bus transportation systems are similar to those of railway transportation systems. Means and dispersions of these restoration functions are given in Tables 7.10.a. Discretized restoration functions are shown in Table 7.10.b, where the percentage restoration is shown at discrete times.

7.4.8 Development of Damage Functions

Fragility curves for bus system components are defined with respect to classification and ground motion parameter.

<u>Damage Functions for Bus System Urban Stations</u>

Urban stations are classified based on the building structural type. Damage functions for bus system urban stations are similar to those for the railway transportation system (see Section 7.2.8).

<u>Damage Functions for Bus System Fuel Facilities</u>

Fuel facilities are classified based on two criteria: (1) whether the sub-components comprising the fuel facilities are anchored or unanchored and (2) whether backup power exists in the facility. Damage functions for bus system fuel facilities are similar to those for the railway transportation system (see Section 7.2.8).

<u>Damage Functions for Bus System Maintenance Facilities</u>

The PGA and PGD median values for the damage states of maintenance facilities are similar to those of light rail maintenance facilities presented in Section 7.3.8.

<u>Damage Functions for Bus System Dispatch Facility</u>

The PGA and PGD median values for the damage states of dispatch facilities are similar to those of railway dispatch facilities given in Section 7.2.8.

7.4.9 Guidance for Loss Estimation using Advanced Data and Models Analysis

For this level of analysis, the expert can use the methodology developed with the flexibility to: (1) include a refined inventory of the bus system pertaining to the area of study, and (2) include component specific and system specific fragility data. Default User-Supplied Data Analysis damage algorithms can be modified or replaced to accommodate any specified key component of a bus system, such as a warehouse. Similarly, better restoration curves could be developed given knowledge of available resources and a more accurate layout of the bus transportation network within the local topographic and geological conditions (i.e., redundancy and importance of a bus system component in the network are known).

7.4.10 References

Applied Technology Council, "Earthquake Damage Evaluation Data for California", ATC-13, Redwood City, CA, 1985.

G & E Engineering Systems, Inc. (G & E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, Transportation Systems", May 1994.

7.5 Port Transportation System

7.5.1 Introduction

This section presents a loss estimation methodology for a port transportation system. Port facilities consist of waterfront structures (e.g., wharfs, piers and seawalls); cranes and cargo handling equipment; fuel facilities; and warehouses. In many cases, these facilities were constructed prior to widespread use of engineered fills; consequently, the wharf, pier, and seawall structures are prone to damage due to soil failures such as liquefaction. Other components may be damaged due to ground shaking as well as ground failure.

7.5.2 Scope

The scope of this section includes developing methods for estimating earthquake damage to a port transportation system given knowledge of components (i.e., waterfront structures, cranes and cargo handling equipment, fuel facilities, and warehouses), classification (i.e. for fuel facilities, anchored or unanchored components, with or without back-up power), and the ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each of the port system components are defined (i.e. slight, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For ports the restoration is dependent upon the extent of damage to the waterfront structures, cranes/cargo handling equipment, fuel facilities, and warehouses. From the standpoint of functionality of the port, the user should consider the restoration of only the waterfront structures and cranes since the fuel facilities and warehouses are not as critical to the functionality of the port.

Fragility curves are developed for each class of port system component. These curves describe the probability of reaching or exceeding a certain damage state given the level of ground motion. Based on these fragility curves, a method for assessing functionality of each of the four port system components is presented.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis that would be performed separately by a port system expert as an advanced study.

7.5.3 Input Requirements and Output Information

Required input to estimate damage to port systems includes the following items:

Waterfront Structures

- Geographic location of port (longitude and latitude)
- PGA & PGD
- Classification

Cranes/Cargo Handling Equipment

- Geographic location of port (longitude and latitude)
- PGA and PGD
- Classification (i.e. stationary or rail mounted)

Fuel Facilities

- Geographical location of facility [longitude and latitude]
- PGA and PGD
- Classification

Warehouses

- Geographical location of warehouse [longitude and latitude]
- PGA and PGD
- Classification (i.e. building type)

Direct damage output for port systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Damage ratios are used as inputs to direct economic loss methods, as described in section 15.3 of Chapter 15.

7.5.4 Form of Damage Functions

Damage functions or fragility curves for all four port system components, mentioned above, are lognormally distributed functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (PGA) and ground failure is quantified in terms of permanent ground displacement (PGD).

- For waterfront structures, the fragility curves are defined in terms of PGD and PGA.

- For cranes/cargo handling equipment, the fragility curves are defined in terms of PGA and PGD.

- For fuel facilities, the fragility curves are defined in terms of PGA and PGD.

- For warehouses, the fragility curves are defined in terms of PGA and PGD.

Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the following section.

7.5.5 Description of Port Components

A port system consists of four components: waterfront structures, cranes/cargo handling equipment, fuel facilities, and warehouses. This section provides a brief description of each.

Waterfront Structures

This component includes wharves (port embankments), seawalls (protective walls from erosion), and piers (break-water structures which form harbors) that exist in the port system. Waterfront structures typically are supported by wood, steel or concrete piles. Many also have batter piles to resist lateral loads from wave action and impact of vessels. Seawalls are caisson walls retaining earth fill material.

Cranes and Cargo Handling Equipment

These are large equipment items used to load and unload freight from vessels. These are can be stationary or mounted on rails.

Port Fuel Facilities

The fuel facility consists mainly of fuel storage tanks, buildings, pump equipment, piping, and, sometimes, backup power. These are the same as those for railway systems presented in Section 7.2. The functionality of fuel systems is determined with a fault tree analysis, which considers redundancies and sub-component behavior, as it can be seen in Figures 7.18 and 7.19 of Section 7.2. Note that five types of fuel facilities in total are defined.

Warehouses

Warehouses are large buildings usually constructed of structural steel. In some cases, warehouses may be several hundred feet from the shoreline, while in other instances; they may be located on the wharf itself.

7.5.6 Definition of Damage States

A total of five damage states are defined for port system components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

<u>Slight/Minor Damage</u> (ds_2)

- <u>For waterfront structures</u>, ds_2 is defined by minor ground settlement resulting in few piles (for piers/seawalls) getting broken and damaged. Cracks are formed on the surface of the wharf. Repair may be needed.

- <u>For cranes/cargo handling equipment</u>, ds_2 is defined by slight damage to structural members with no loss of function for the stationary equipment, while for the unanchored or rail mounted equipment, ds_1 is defined as minor derailment or misalignment without any major structural damage to the rail mount. Minor repair and adjustments may be required before the crane becomes operable.

- <u>For fuel facilities</u>, ds_2 is defined the same as for railway facilities.

- <u>For warehouses</u>, ds_2 is defined by slight damage to the warehouse building.

<u>Moderate Damage</u> (ds_3)

- <u>For waterfront structures</u>, ds_3 is defined as considerable ground settlement with several piles (for piers/seawalls) getting broken and damaged.

- <u>For cranes/cargo handling equipment</u>, ds_3 is defined as derailment due to differential displacement of parallel track. Rail repair and some repair to structural members is required.

- <u>For fuel facilities</u>, ds_3 is defined the same as for railway facilities.

- <u>For warehouses</u>, ds_3 is defined by moderate damage to the warehouse building.

<u>Extensive Damage</u> (ds_4)

- <u>For waterfront structures</u>, ds_4 is defined by failure of many piles, extensive sliding of piers, and significant ground settlement causing extensive cracking of pavements.

- <u>For cranes/cargo handling equipment</u>, ds_4 is defined by considerabe damage to equipment. Toppled or totally derailed cranes are likely to occcur. Replacement of structural members is required.

- <u>For fuel facilities</u>, ds_4 is defined same as for railway facilities.

- <u>For warehouses</u>, ds_4 is defined by extensive damage to warehouse building.

<u>Complete Damage</u> (ds_5)

- <u>For waterfront structures</u>, ds_5 is defined as failure of most piles due to significant ground settlement. Extensive damage is widespread at the port facility.

- For cranes/cargo handling equipment, ds_5 is the same as ds_4.
- For fuel facilities with buried tanks, ds_5 is the same as for railway facilities.
- For warehouses, ds_5 is defined by total damage to the warehouse building.

7.5.7 Component Restoration Curves

Restoration Curves are developed based on a best fit to ATC-13 damage data for social functions SF 28.a and SF 29.b, consistent with damage states defined in the previous section. Normal distribution functions are developed using the ATC-13 data for the mean time for 30%, 60% and 100% restoration of different sub-components in different damage states. Means and dispersions of these restoration functions are given in Table 7.14.a. The discretized restoration functions are given in Table 7.14.b, where the percentage restoration is shown at some specified time intervals. These restoration functions are shown in Figures 7.23 and 7.24. Figure 7.23 represents restoration curves for waterfront structures, while Figure 7.24 shows restorations curve for cranes and cargo handling equipment.

Table 7.14.a Restoration Functions for Port Sub-Components

Restoration Functions (All Normal Distributions)			
Classification	**Damage State**	**Mean (Days)**	**σ**
Buildings, Waterfront Structures	slight/minor	0.6	0.2
	moderate	3.5	3.5
	extensive	22	22
	complete	85	73
Cranes/Cargo Handling Equipment	slight/minor	0.4	0.35
	moderate	6	6
	extensive	30	30
	complete	75	55

Table 7.14.b Discretized Restoration Functions for Port Sub-Components

Discretized Restoration Functions						
Classification	**Damage State**	**1 day**	**3 days**	**7 days**	**30 days**	**90 days**
Buildings, Waterfront Structures	slight/minor	96	100	100	100	100
	moderate	24	43	84	100	100
	extensive	17	19	25	63	100
	complete	12	13	14	22	53
Cranes/Cargo Handling Equipment	slight/minor	96	100	100	100	100
	moderate	20	31	57	100	100
	extensive	17	18	22	50	100
	complete	9	10	11	21	62

7.5.8 Development of Damage Functions

Damage functions for port system facilities are defined in terms of PGA and PGD. Note that, unless it is specified otherwise, ground failure (PGD) related damage functions for these facilities are assumed to be similar to those described for railroad system facilities in section 7.2.8.

An example of how to combine PGD and PGA algorithms is presented in section 7.2.8.

Damage functions for Waterfront Structures

Damage functions for waterfront structures were established based on damagability of subcomponents, namely, piers, seawalls, and wharf. Fault tree logic and the lognormal best fitting technique were used in developing these fragility curves. The fault tree is implicitly described in the description of the damage state. The obtained damage functions are shown in Figure 7.25. Their medians and dispersions are presented in Table 7.15a. Subcomponent damage functions are given in Table 7.D.1 of Appendix 7D.

Table 7.15.a Damage Algorithms for Waterfront Structures

Permanent Ground Deformation			
Components	**Damage State**	**Median (in)**	**β**
Waterfront Structures (PWS1)	slight/minor	5	0.50
	moderate	12	0.50
	extensive	17	0.50
	complete	43	0.50

Damage Functions for Cranes and Cargo Handling Equipment

For cranes, a distinction is made between stationary and rail-mounted cranes. The medians and dispersions of damage functions are presented in Tables 7.15.b, while the fragility curves are shown in Figures 7.26 through 7.29.

Table 7.15.b Damage Algorithms for Cranes/Cargo Handling Equipment

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Anchored/ Stationary (PEQ1)	slight/minor	0.3	0.6
	moderate	0.5	0.6
	extensive/complete	1.0	0.7
Unanchored/Rail mounted (PEQ2)	slight/minor	0.15	0.6
	moderate	0.35	0.6
	extensive/complete	0.8	0.7

Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
Anchored/ Stationary (PEQ1)	slight/minor	3	0.6
	moderate	6	0.7
	extensive/complete	12.0	0.7
Unanchored/Rail mounted (PEQ2)	slight/minor	2	0.6
	moderate	4.0	0.6
	extensive/complete	10	0.7

Damage Functions for Port System Fuel Facilities

Damage funcitons for fuel facilities are similar to those developed for railway fuel facilities in Section 7.2.8.

PGA Related Damage Functions for Warehouses

Since no default inventory is provided for these facilities, the user will be expected to provide the appropriate mapping bewteen these facilities and the building types which are assumed to be the same as for railway maintenance facilities whose damage functions are listed in Table 7.7 of section 7.2.8.

7.5.9 Guidance for Loss Estimation using Advanced Data and Models Analysis

For this type of analysis, the expert can use the methodology developed with the flexibility to: (1) include a refined inventory of the port transportation system pertaining to the area of study, and (2) include component specific and system specific fragility data. Default User-Supplied Data Analysis damage algorithms can be modified or replaced to accommodate any specified key component of a port system, such as a warehouse. Similarly, better restoration curves could be developed given knowledge of available resources and a more accurate layout of the port network within the local topographic and geological conditions (i.e., redundancy and importance of a port system component in the network are known).

7.5.10 References

Applied Technology Council, "Earthquake Damage Evaluation Data for California", ATC-13, Redwood City, CA, 1985.

G & E Engineering Systems, Inc. (G & E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, Transportation Systems", May 1994.

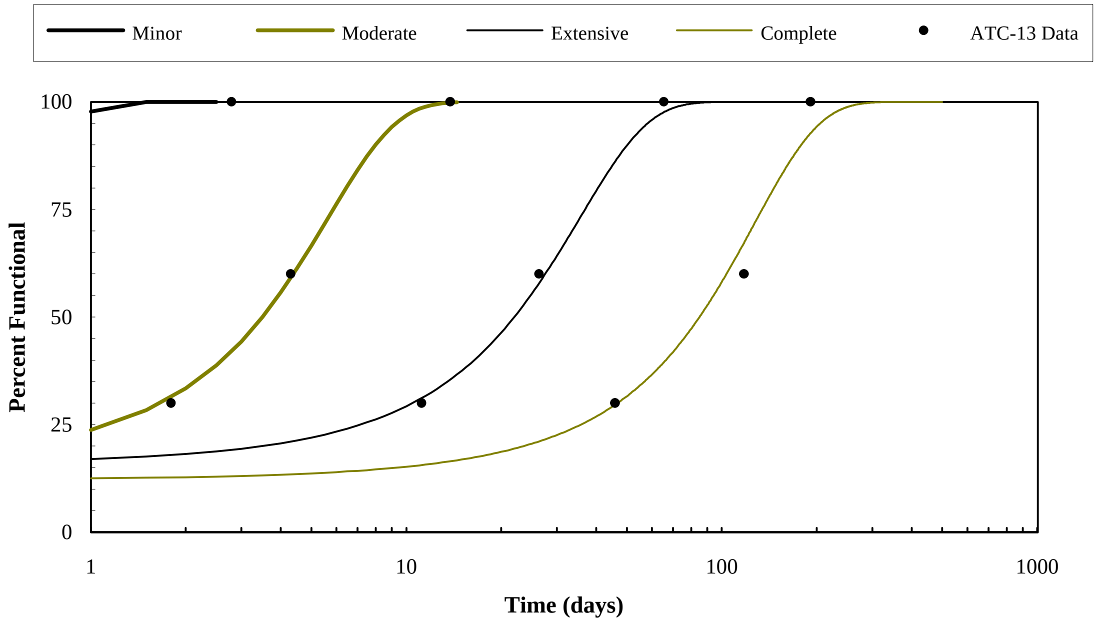


Figure 7.23 Restoration Curves for Port Waterfront Structures.

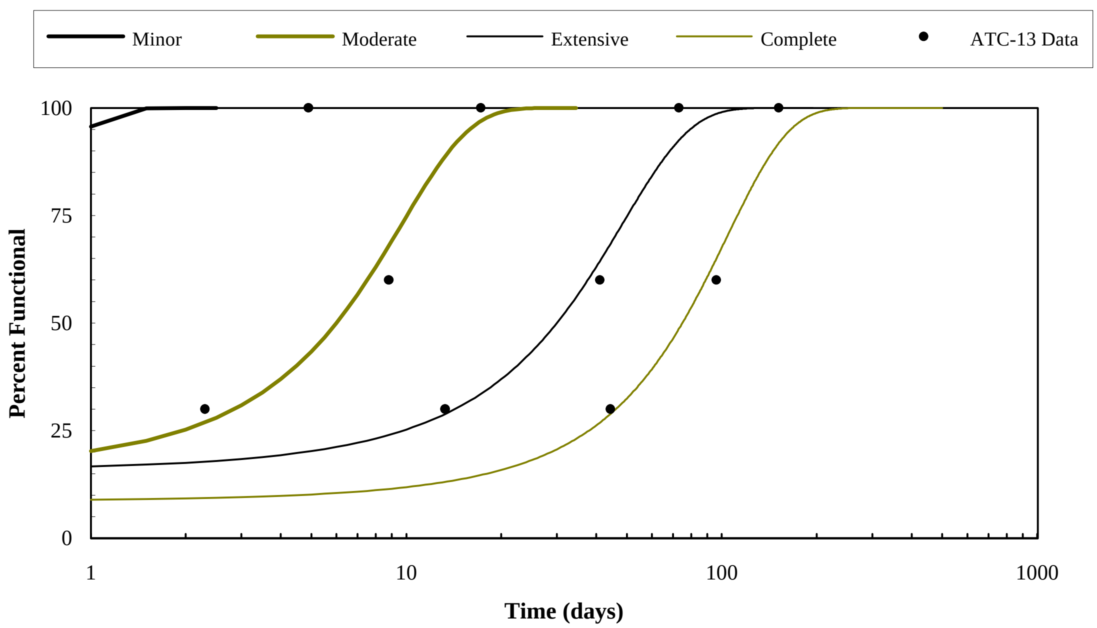


Figure 7.24 Restoration Curves for Cranes/Cargo Handling Equipment.

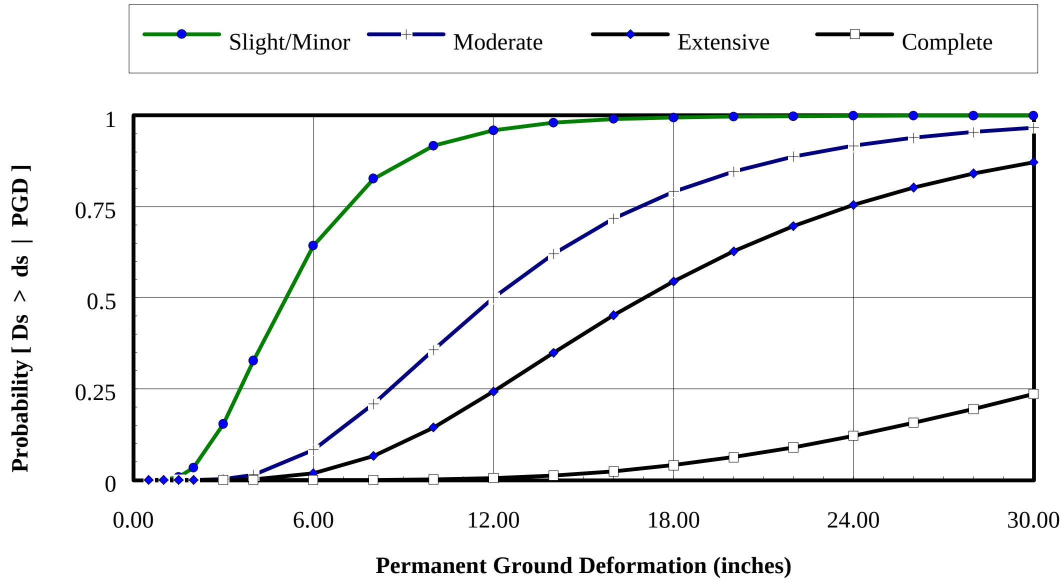


Figure 7.25 Fragility Curves for Waterfront Structures.

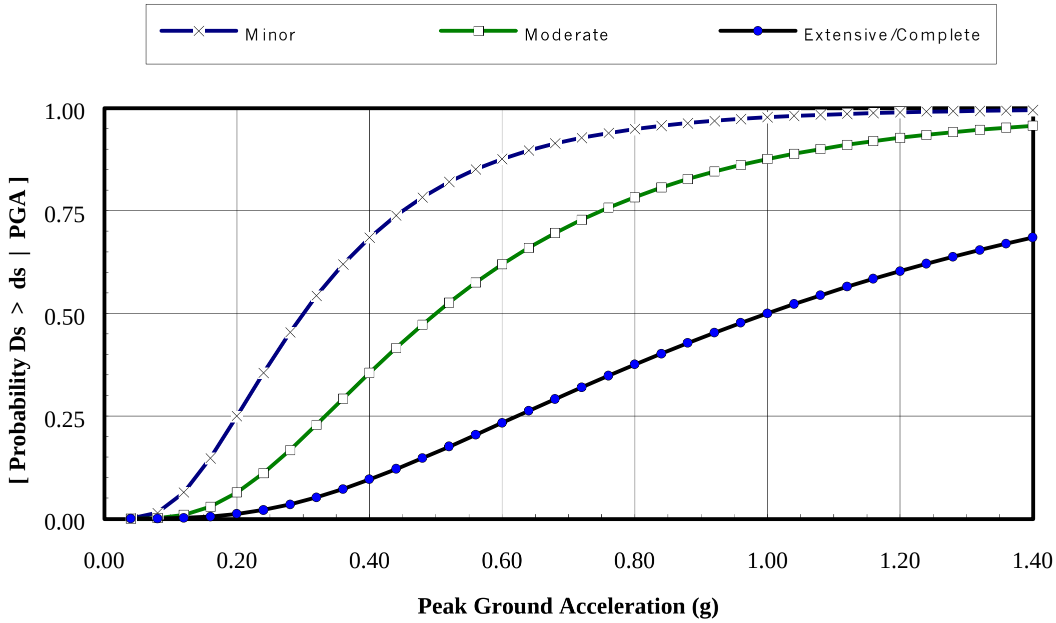


Figure 7.26 Fragility Curves for Stationary Cranes/Cargo Handling Equipment Subject to Peak Ground Acceleration.

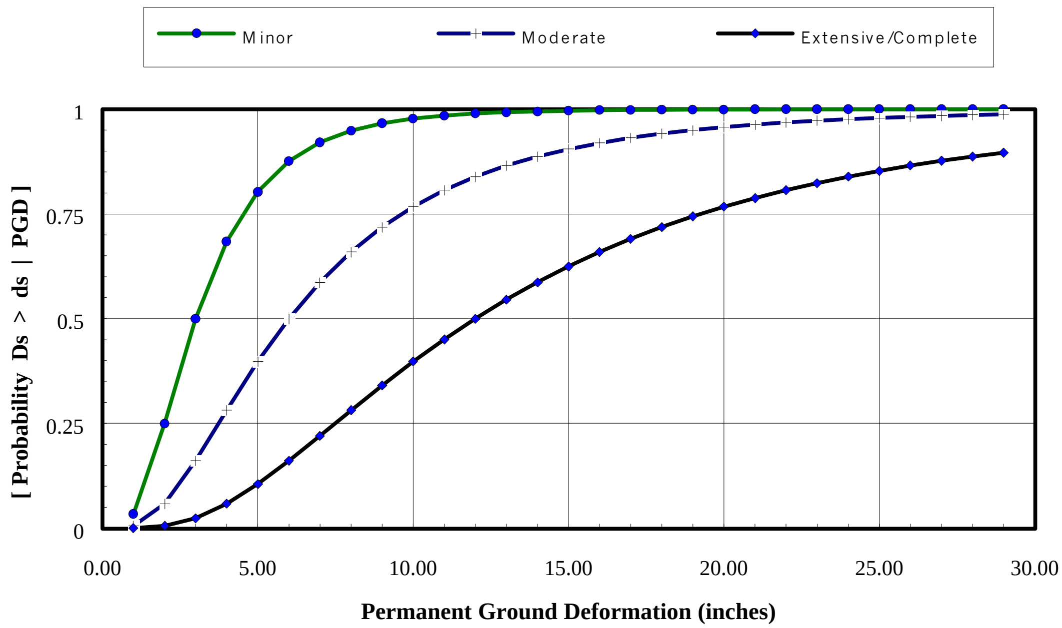


Figure 7.27 Fragility Curves for Stationary Cranes/Cargo Handling Equipment Subject to Permanent Ground Deformation.

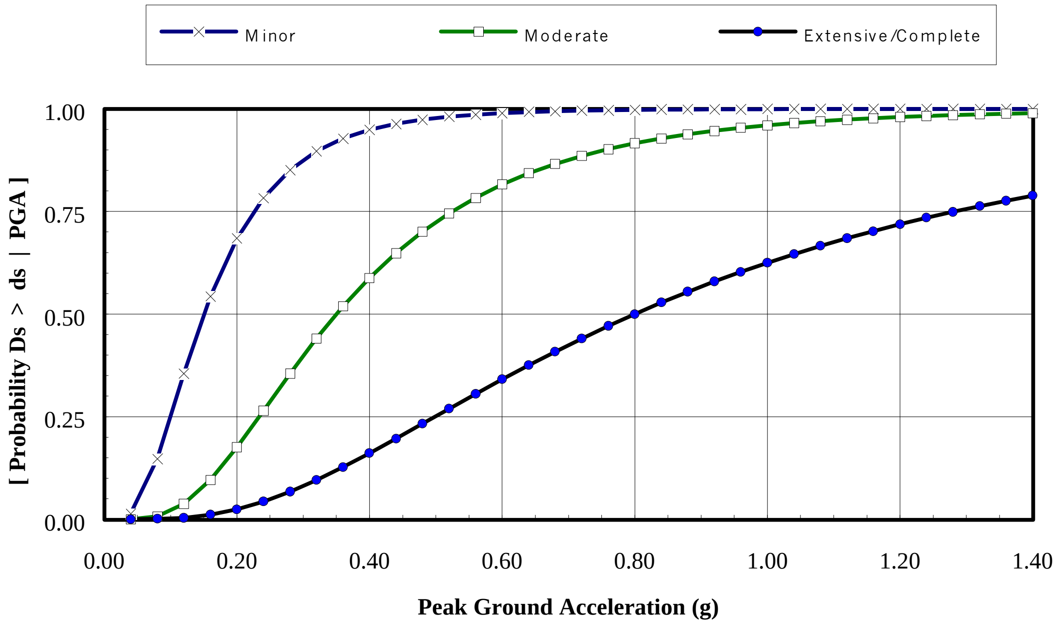


Figure 7.28 Fragility Curves for Rail Mounted Cranes/Cargo Handling Equipment Subject to Peak Ground Acceleration.

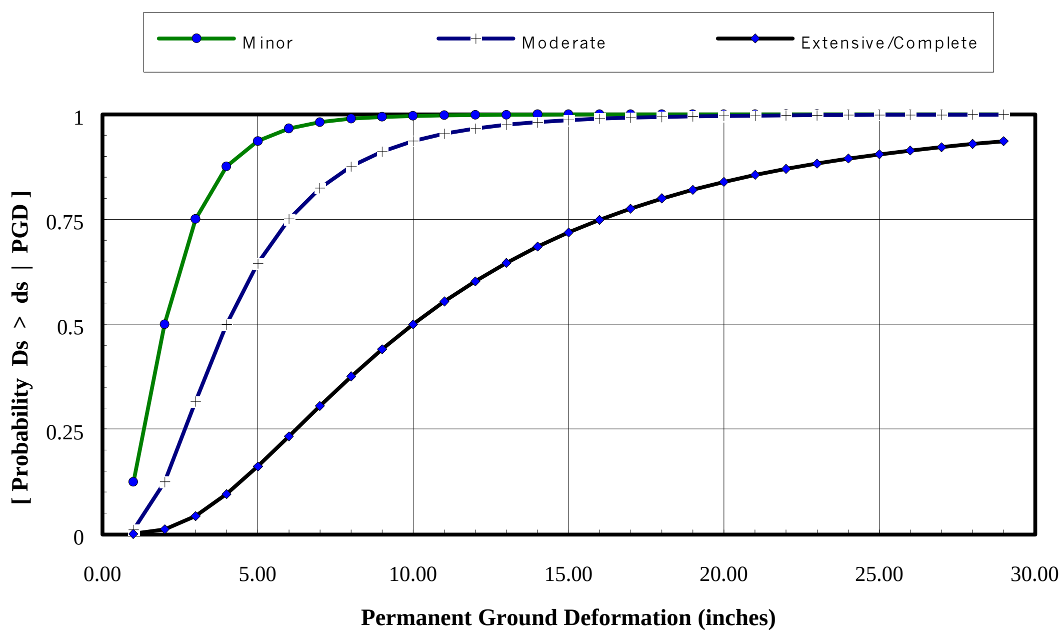


Figure 7.29 Fragility Curves for Rail Mounted Cranes/Cargo Handling Equipment Subject to Permanent Ground Deformation.

7.6 Ferry Transportation System

7.6.1 Introduction

This section presents a loss estimation methodology for a ferry transportation system. Ferry systems consist of waterfront structures (e.g., wharf, piers and seawalls); fuel, maintenance, and dispatch facilities; and passenger terminals.

The waterfront structures are located at the points of embarkation or disembarkation, and they are similar to, although not as extensive as, those of the port transportation system. In some cases the ferry system may be located within the boundary of the port transportation system. The points of embarkation or disembarkation are located some distance apart from one another, usually on opposite shorelines.

Fuel and maintenance facilities are usually located at one of these two points. The size of the fuel facility is smaller than that of the port facility. In many cases, the dispatch facility is located in the maintenance facility or one of the passenger terminals.

7.6.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a ferry transportation system given knowledge of components (i.e., waterfront structures; fuel, maintenance, and dispatch facilities; and passenger terminals), classification (i.e. for fuel facilities, anchored or unanchored components, with or without back-up power), and the ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each of the ferry system components are defined (i.e. slight/minor, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For ferries the restoration is dependent upon the extent of damage to the waterfront structures; fuel, maintenance, and dispatch facilities; and passenger terminals.

Fragility curves are developed for each class of the ferry system components. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion. Based on these fragility curves, a method for assessing functionality of each of the five ferry system components is presented.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis that would be performed separately by a transportation system expert as an advanced study.

7.6.3 Input Requirements and Output Information

Required input to estimate damage to ferry systems includes the following items:

<u>Ferry Waterfront Structures</u>
- Geographic locations of harbor
- PGA & PGD

<u>Ferry Fuel Facilities</u>
- Geographical location of facility
- PGA and PGD
- Classification

<u>Ferry Maintenance Facilities</u>
- Geographical location of facility
- PGA and PGD
- Classification (i.e. building type)

<u>Ferry Dispatch Facilities</u>
- Geographical location of facility
- PGA and PGD
- Classification

<u>Ferry Terminal Buildings</u>
- Geographical location of building
- PGA and PGD
- Classification (i.e. building type)

Direct damage output for ferry systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Damage ratios are used as inputs to direct economic loss methods, as described in section 15.3 of Chapter 15.

7.6.4 Form of Damage Functions

Damage functions or fragility curves for all five ferry system components mentioned above, are lognormal functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (PGA) and ground failure is quantified in terms of permanent ground displacement (PGD).

- For waterfront structures, the fragility curves are defined in terms of PGA & PGD.
- For fuel facilities, maintenance and dispatch facilities; and terminal building, the fragility curves are defined in terms of PGA and PGD.

Definitions of various damage states and the methodology used in deriving fragility curves for ferry system components are presented in the following subsections.

7.6.5 Description of Ferry System Components

A ferry system consists of the five components mentioned above: waterfront structures, fuel facilities, maintenance facilities, dispatch facilities, and passenger terminals. This section provides a brief description of each.

Waterfront Structures
These are the same as those for port systems described in Section 7.5.5.

Fuel Facilities
These facilities are similar to those for port system mentioned in Section 7.5.5.

Maintenance Facilities
These are often steel braced frame structures, but other building types are possible.

Dispatch Facilities
These are similar to those defined for railway system in Section 7.2.5.

Passenger Terminals
These are often moment resisting steel frames, but other building types are possible.

7.6.6 Definitions of Damage States

A total of five damage states are defined for ferry system components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

Slight/Minor Damage (ds_2)

- For waterfront structures, ds_2 is the same as that for waterfront structures in the port module.
- For fuel facilities, ds_2 is the same as that for fuel facilities in the port module.
- For maintenance facilities, ds_2 is defined by slight damage to building.

- For dispatch facilities, ds_2 is the same as that for dispatch facilities in the railway module.
- For passenger terminals, ds_2 is defined by slight damage to building.

Moderate Damage (ds_3)

- For waterfront structures, ds_3 is the same as that for waterfront structures in the port module.
- For fuel facilities, ds_3 is the same as that for fuel facilities in the port module.
- For maintenance facilities, ds_3 is defined by moderate damage to building.
- For dispatch facilities, ds_3 is the same as that for dispatch facilities in the railway module.
- For passenger terminals, ds_3 is defined by moderate damage to building.

Extensive Damage (ds_4)

- For waterfront structures, ds_4 is the same as that for waterfront structures in the port module.
- For fuel facilities, ds_4 is the same as that for fuel facilities in the port module.
- For maintenance facilities, ds_4 is defined by extensive damage to building.
- For dispatch facilities, ds_4 is the same as that for dispatch facilities in the railway module.
- For passenger terminals, ds_4 is defined by extensive damage to building.

Complete Damage (ds_5)

- For waterfront structures, ds_5 is the same as that for waterfront structures in the port module.
- For fuel facilities, ds_5 is the same as that for fuel facilities in the port module.
- For maintenance facilities, ds_5 is defined by complete damage to building.
- For dispatch facilities, ds_5 is the same as that for dispatch facilities in the railway module.

- For passenger terminals, ds_5 is defined as complete damage to building.

7.6.7 Component Restoration Curves

Ferry systems are made of components that are similar to either those in port systems (i.e. waterfront structures, fuel facilities), or those in railway systems (i.e. dispatch facilities, maintenance facilities, passenger terminals). Therefore, restoration curves for ferry system components can be found in either Section 7.5 or Section 7.2.

7.6.8 Development of Damage Functions

Similar to restoration curves, damage functions for ferry system components can be found in either Section 7.5 or Section 7.2.

7.6.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For this type of analysis, the expert can use the methodology developed with the flexibility to: (1) include a refined inventory of the ferry system pertaining to the area of study, and (2) include component specific and system specific fragility data. Default User-Supplied Data Analysis damage algorithms can be modified or replaced to accommodate any specified key component of a ferry system, such as a maintenance facility. Similarly, better restoration curves could be developed given knowledge of available resources and a more accurate layout of the ferry transportation network within the local topographic and geological conditions.

7.6.10 References

Applied Technology Council, "Earthquake Damage Evaluation Data for California", ATC-13, Redwood City, CA, 1985.

G & E Engineering Systems, Inc. (G & E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, Transportation Systems", May 1994.

7.7 Airport Transportation System

7.7.1 Introduction

This section presents a loss estimation methodology for an airport transportation system. Airport transportation system consists of runways, control tower, fuel facilities, terminal buildings, maintenance facilities, hangar facilities, and parking structures. For airports, control towers are often constructed of reinforced concrete, while terminal buildings and maintenance facilities are often constructed of structural steel or reinforced concrete. Fuel facilities are similar to those for railway transportation systems.

7.7.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to an airport transportation system given knowledge of components (i.e. runways, control tower, fuel, and maintenance facilities, terminal buildings, and parking structures), classification, and ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each of the airport system components are defined (i.e. slight, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For airports, the restoration is dependent upon the extent of damage to the airport terminals, buildings, storage tanks (for fuel facilities), control tower, and runways.

Fragility curves are developed for each component class of the airport system. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion. Based on these fragility curves, a method for assessing functionality of each of the six airport system components is presented.

7.7.3 Input Requirements and Output Information

Required input to estimate damage to airport systems includes the following items:

Runways

- Geographic location of airport [longitude and latitude]
- PGD

Control Tower

- Geographic location of airport [longitude and latitude]

- PGA and PGD
- Classification (i.e. building type)

Fuel Facilities

- Geographical location of facility [longitude and latitude]
- PGA and PGD
- Classification

Terminal Buildings

- Geographical location of airport [longitude and latitude]
- PGA and PGD
- Classification (i.e. building type)

Maintenance and Hangar Facilities

- Geographical location of facility [longitude and latitude]
- PGA and PGD
- Classification (i.e. building type)

Parking Structures

- Geographical location of structure [longitude and latitude]
- PGA and PGD
- Classification (i.e. building type)

Direct damage output for airport systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Damage ratios are used as inputs to direct economic loss methods, as described in section 15.3 of Chapter 15.

7.7.4 Form of Damage Functions

Damage functions or fragility curves for all five airport system components mentioned above, are lognormal functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (PGA) and ground failure is quantified in terms of permanent ground displacement (PGD).

- For runways, the fragility curves are defined in terms of PGD.

- For control towers, the fragility curves are defined in terms of PGA and PGD.

- For all other facilities, the fragility curves are defined in terms of PGA and PGD.

Definitions of various damage states and the methodology used in deriving these fragility curves are presented in the following section.

7.7.5 Description of Airport Components

An airport system consists of the six components mentioned above: runways, control tower, fuel facilities, maintenance facilities, and parking structures. This section provides a brief description of each.

Runways
This component consists of well-paved "flat and wide surfaces".

Control Tower
Control tower consists of a building and the necessary equipment of air control and monitoring.

Fuel Facilities
These have been previously defined in Section 7.2.5 of railway systems.

Terminal Buildings
These are similar to urban stations of railway systems from the classification standpoint (as well as services provided to passengers).

Maintenance Facilities, Hangar Facilities, and Parking Structures
Classification of maintenance facilities is the same as for those in railway systems. Hangar facilities and parking structures are mainly composed of buildings.

7.7.6 Definitions of Damage States

A total of five damage states are defined for airport system components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

Slight/Minor Damage (ds_2)

- For runways, ds_2 is defined as minor ground settlement or heaving of runway surface.

- For control tower, ds_2 is defined as slight damage to the building as given in section 5.3.

- For fuel facilities, ds_2 is the same as that for fuel facilities in the railway module.
- For terminal buildings, ds_2 is defined as slight damage to the building as given in section 5.3.
- For maintenance and hangar facilities, ds_2 is defined as slight damage to the building as given in section 5.3.
- For parking structures, ds_2 is defined as slight damage to the building as given in section 5.3.

Moderate Damage (ds_3)

- For runways, ds_3 is defined same as ds_2.
- For control tower, ds_3 is defined as moderate damage to the building as given in section 5.3.
- For fuel facilities, ds_3 is the same as that for fuel facilities in the railway module.
- For terminal buildings, ds_3 is defined as moderate damage to the building as given in section 5.3.
- For maintenance and hangar facilities, ds_3 is defined as moderate damage to the building as given in section 5.3.
- For parking structures, ds_3 is defined as moderate damage to the building as given in section 5.3.

Extensive Damage (ds_4)

- For runways, ds_4 is defined as considerable ground settlement or considerable heaving of runway surface.
- For control tower, ds_4 is defined as extensive damage to the building as given in section 5.3.
- For fuel facilities, ds_4 is the same as that for fuel facilities in the railway module.
- For terminal buildings, ds_4 is defined as extensive damage to the building as given in section 5.3.
- For maintenance and hangar facilities, ds_4 is defined as extensive damage to the building as given in section 5.3.

- For parking structures, ds_4 is defined as extensive damage to the building as given in section 5.3.

Complete Damage (ds_5)

- For runways, ds_5 is defined as extensive ground settlement or excessive heaving of runway surface.
- For control tower, ds_5 is defined as complete damage to the building as given in section 5.3.
- For fuel facilities, ds_5 is the same as that for fuel facilities in the railway module.
- For terminal buildings, ds_5 is defined as complete damage to the building as given in section 5.3.
- For maintenance and hangar facilities, ds_5 is defined as complete damage to the building as given in section 5.3.
- For parking structures, ds_5 is defined as complete damage to the building as given in section 5.3.

7.7.7 Component Restoration Curves

Restoration Curves are developed based on a best fit to ATC-13 data for social functions SF 27.a and SF 27.b, consistent with damage states defined in the previous section. Normal distribution functions are developed using this ATC-13 data for the mean time for 30%, 60% and 100% restoration. Means and dispersions of these restoration functions are given in Table 7.16.a and shown in Figures 7.30 and 7.31. The discretized restoration functions are presented in Table 7.16.b, where the percentage restoration is shown at selected time intervals.

Table 7.16.a Restoration Functions for Airport Components

Restoration Functions (All Normal Distributions)			
Classification	**Damage State**	**Mean (Days)**	**σ**
Control Towers, Parking Structures, Hangar Facilities, Terminal Building	slight moderate extensive complete	0 1.5 50 150	0 1.5 50 120
Runways	slight/moderate extensive complete	2.5 35 85	2.5 35 65

Table 7.16.b Discretized Restoration Functions for Aiport Sub-Components

Discretized Restoration Functions						
Classification	**Damage State**	**1 day**	**3 days**	**7 days**	**30 days**	**90 days**
Control Towers, Parking Structures, Hangar Facilities, Terminal Building	slight	100	100	100	100	100
	moderate	37	84	100	100	100
	extensive	16	17	20	34	79
	complete	11	11	12	16	31
Runways	slight/moderate	27	57	100	100	100
	extensive	17	18	21	44	95
	complete	10	11	12	20	53

7.7.8 Development of Damage Functions

Damage functions for airport system facilities are defined in terms of PGA and PGD except for runways (PGD only). Note that, unless it is specified otherwise, ground failure (PGD) related damage functions for these facilities are assumed to be similar to those described for railroad system facilities in section 7.2.8.

An example of how to combine PGD and PGA algorithms is presented in section 7.2.8.

Damage Functions for Runways

The earthquake hazard for airport runways is ground failure. Little damage is attributed to ground shaking; therefore, the damage function includes only ground failure as the hazard. All runways are assumed to be paved. The median values and dispersion for the damage states for runways are given in Table 7.17. These damage functions are also shown in Figure 7.32.

Table 7.17 Damage Algorithms for Runways

Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
Runways	slight/moderate	1	0.6
	extensive	4	0.6
	complete	12	0.6

Damage Functions for Rest of Airport System Components

In section 7.7.5, these components were defined by "one to one" correspondence with those for railway systems. Therefore, damage functions for the remaining airport components (i.e. fuel facilities, maintenance facilities, and other buildings) can be found in Section 7.2.8.

7.7.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For this level of analysis, the expert can use the methodology developed with the flexibility to: (1) include a refined inventory of the airport system pertaining to the area of study, and (2) include component specific and system specific fragility data. Default User-Supplied Data Analysis damage algorithms can be modified or replaced to accommodate any specified key component of a airport system, such as a control tower. Similarly, better restoration curves could be developed given knowledge of available resources and a more accurate layout of the transportation network within the local topographic and geological conditions.

7.7.10 References

Applied Technology Council, "Earthquake Damage Evaluation Data for California", ATC-13, Redwood City, CA, 1985.

G & E Engineering Systems, Inc. (G & E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, Transportation Systems (Airport Systems)", May 1994.

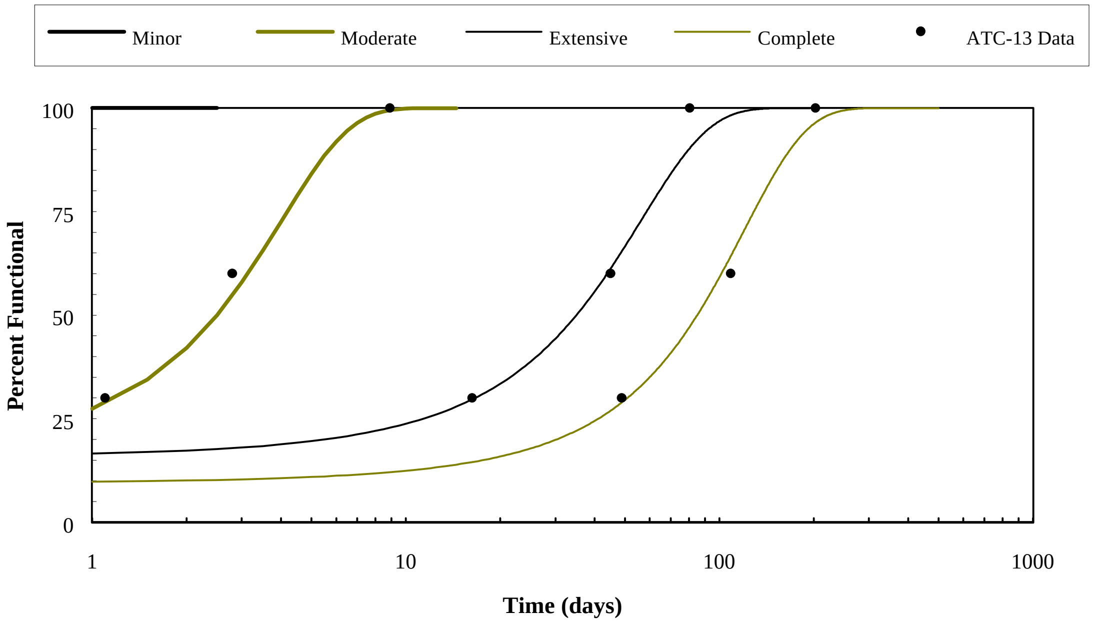


Figure 7.30 Restoration Curve for Airport Runways.

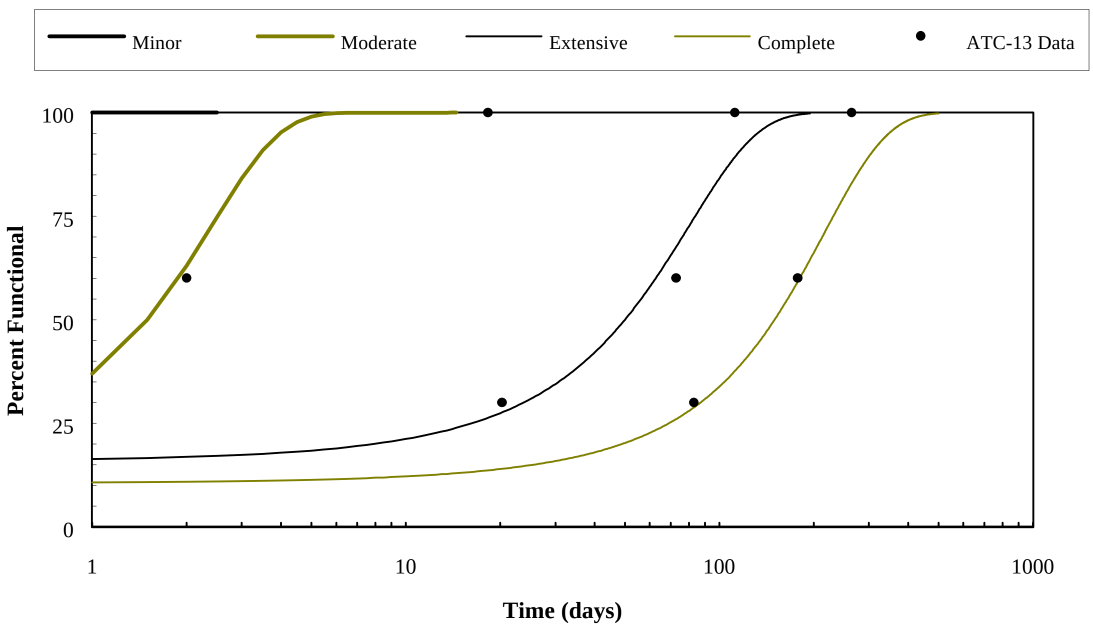


Figure 7.31 Restoration Curves for Airport Buildings, Facilities, and Control Tower.

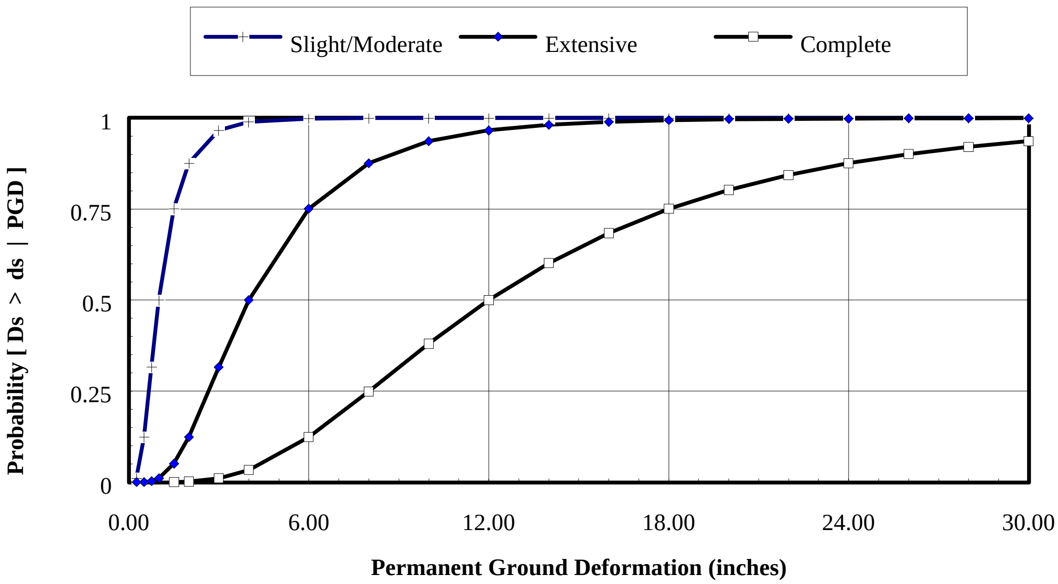


Figure 7.32 Fragility Curves for Runways Subject to Permanent Ground Deformation at Various Damage States.

APPENDIX 7A

Any given subcomponent in the lifeline methodology can experience all five damage states; however, the only damage states listed in the appendices of Chapters 7 and 8 are the ones used in the fault tree logic of the damage state of interest of the component.

Table A.7.1 Subcomponent Damage Algorithms: Rock Tunnels (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	Damage State	Median (g)	β
Liner	slight moderate	0.6 0.8	0.4 0.6

Permanent Ground Deformation			
Subcomponents	Damage State	Median (in)	β
Liner	slight extensive complete	6 12 60	0.7 0.5 0.5
Portal	slight extensive complete	6 12 60	0.7 0.5 0.5

Table A.7.2 Subcomponent Damage Algorithms: Cut & Cover Tunnels (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	Damage State	Median (g)	β
Liner	slight moderate	0.5 0.7	0.4 0.6

Permanent Ground Deformation			
Subcomponents	Damage State	Median (in)	β
Liner	slight extensive complete	6 12 60	0.7 0.5 0.5
Portal	slight extensive complete	6 12 60	0.7 0.5 0.5

APPENDIX 7B

Table B.7.1 Subcomponent Damage Algorithms: Seismically Designed Railway Bridges (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Column	slight	0.45	0.55
	extensive	1.0	0.7
	complete	1.4	0.7
Abutment	slight	0.45	0.55
	moderate	1.0	0.7
Connection	moderate	0.86	0.70
	extensive	1.4	0.70
Deck	slight	0.67	0.55

Permanent Ground Deformation			
Subcomponents	**Damage State**	**Median (in)**	**β**
Column	extensive	14	0.7
	complete	28	0.7
Abutment	moderate	15	0.7
	extensive	30	0.7
Connection	complete	30	0.7
Approach	slight	2	0.5
	moderate	12	0.7
	extensive	24	0.7

Table B.7.2 Subcomponent Damage Algorithms: Conventionally Designed Railway Bridges (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Column	slight extensive complete	0.3 0.8 1.0	0.55 0.7 0.7
Abutment	slight moderate	0.3 0.8	0.55 0.7
Connection	moderate extensive	0.7 1.0	0.70 0.70
Deck	slight	0.5	0.55

Permanent Ground Deformation			
Subcomponents	**Damage State**	**Median (in)**	**β**
Column	extensive complete	10 21	0.7 0.7
Abutment	moderate extensive	10 21	0.7 0.7
Connection	complete	21	0.7
Approach	slight moderate extensive	2 12 24	0.5 0.7 0.7

**Table B.7.3 Subcomponent Damage Algorithms:
Fuel Facility with Anchored Components (after G&E, 1994)**

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	slight moderate	0.80 1.00	0.60 0.80
Electric Power (Off-Site)	slight moderate	0.15 0.25	0.6 0.5
Tank	slight moderate extensive complete	0.30 0.70 1.25 1.60	0.60 0.60 0.65 0.60
Pump Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Horizontal Pump	extensive	1.60	0.60
Equipment	moderate	1.00	0.60

**Table B.7.4 Subcomponent Damage Algorithms:
Fuel Facility with Unanchored Components (after G&E, 1994)**

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	slight moderate	0.20 0.40	0.60 0.80
Electric Power (Off-Site)	slight moderate	0.15 0.25	0.6 0.5
Tank	slight moderate extensive complete	0.15 0.35 0.68 0.95	0.70 0.75 0.75 0.70
Pump Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Horizontal Pump	extensive	1.60	0.60
Equipment	moderate	0.60	0.60

Table B.7.5 Subcomponent Damage Algorithms: Dispatch Facility with Anchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	slight moderate	0.80 1.00	0.60 0.80
Electric Power (Off-Site)	slight moderate	0.15 0.25	0.6 0.5
Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Equipment	moderate	1.00	0.60

Table B.7.6 Subcomponent Damage Algorithms: Dispatch Facility with Unanchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	slight moderate	0.20 0.40	0.60 0.80
Electric Power (Off-Site)	slight moderate	0.15 0.25	0.6 0.5
Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Equipment	moderate	0.60	0.60

APPENDIX 7C

Table C.7.1 Subcomponent Damage Algorithms for DC Power Substation with Anchored Components

Peak Ground Acceleration			
Subcomponents	Damage State	Median (g)	β
Building	slight	0.15	0.80
	moderate	0.40	0.80
	extensive	0.80	0.80
	complete	1.50	0.80
Equipment	moderate	1.00	0.60
Off-Site Power	slight	0.15	0.6
	moderate	0.25	0.5

Table C.7.2 Subcomponent Damage Algorithms for DC Power Substation with Unanchored Components

Peak Ground Acceleration			
Subcomponents	Damage State	Median (g)	β
Building	slight	0.15	0.80
	moderate	0.40	0.80
	extensive	0.80	0.80
	complete	1.50	0.80
Equipment	moderate	0.60	0.60
Off-Site Power	slight	0.15	0.6
	moderate	0.25	0.5

APPENDIX 7D

Table 7.D.1 Subcomponent Damage Algorithms for Waterfront Structures

Permanent Ground Deformation			
Subcomponents	**Damage State**	**Median (in)**	**β**
Wharf	slight	8	0.6
Piers	slight	8	0.6
	moderate	16	0.6
	extensive	24	0.6
	complete	60	0.6
Seawalls	slight	8	0.6
	moderate	16	0.6
	extensive	24	0.6
	complete	60	0.6